HAMILTON HARBOUR STUDY

1977

Volume I

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Water Modelling Section

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HAMILTON HARBOUR STUDY

1977

Volume I

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HAMILTON HARBOUR REPORT

SUMMARY

The studies in Hamilton Harbour in 1977 were a continuation of studies from earlier years. (MOE 1975, 1977, 1978.) In addition to the work carried out by the Water Resources Branch, investigations of plankton densities and speciation and their correlation with nutrient concentration and light regimes were done under a contract by Dr. G. Harris of McMaster University. An extensive study of loadings to the Harbour from industry, municipal sewage treatment plants, tributaries and storm sewers was compiled under a contract by Dr. W. Snodgrass of McMaster University. This is included as Volume II of this report. The main findings are summarized below.

VOLUME I

A. ARTIFICIAL MIXING

Operationally, this was the best year to date, although the airflow was below the estimated critical level required for successful turnover of the water column and reaeration. The results expected were: an increase in dissolved oxygen levels; reduction in the levels of dissolved heavy metals, nutrients and dissolved organics; and improved light penetration.

The results of the bi-weekly sampling for water quality in the Harbour did not show any evidence that the temperature and oxygen profiles had been affected by the mixing. The hypolimnion oxygen concentration increased at the end of July as it had in previous years.

No relationships between mixing and the concentrations of other water quality parameters such as nutrients, suspended solids, phytoplankton and bacteria could be observed. The one possible exception was the increase in the number of nitrogen cycle bacteria.

B. OXYGEN BUDGET

The average oxygen stocks in the Harbour were the same as in previous years, reaching a minimum in early July when the epiliminion was also undersaturated. The lenses of oxygen-rich water in the hypolimnion during June and July are, in all likelihood, lake water entering via the Burlington Canal.

The vertical turbulent fluxes of oxygen were calculated for different seasons using a model which divides the Harbour vertically into layers of equal thickness. The layers are considered as horizontally homogeneous. The vertical diffusion coefficient, D, was calculated from the fluxes and the known oxygen gradients. A very pronounced minimum in D was found at the thermocline, but, because of the high oxygen gradients, the oxygen flux was still considerable and at no time during the summer was the hypolimnion effectively isolated from the epilimnion.

A simple single box predictive model for oxygen concentrations was developed, using sediment oxygen demand and water column oxygen demand as sinks and reaeration, photosynthesis and lake-harbour exchange as sources. Quite good agreement between predicted and observed mean oxygen concentrations was achieved. The model suggests that to reach an oxygen concentration of 5 mg/L, which is the Ontario objective for the protection of warm-water biota at temperatures between 10^{o}C and 20^{o}C the water column demand should be reduced by 20%.

C. WATER CHEMISTRY

In 1976 and 1977, four stations were sampled approximately bi-weekly to determine trends in water quality, the oxygen budget and the effects of abatement procedures. In addition, depth profiles of temperature, oxygen, Eh, pH and conductivity were measured weekly. In 1977 a survey of stormwater runoff at 12 locations in the harbour was done.

Oxygen has already been dealt with in Section B. Of the nutrients, ammonia was much higher in the spring of 1977 than in the previous two years. The source is apparently the Hamilton Sewage Treatment Plant. The year-to-year or seasonal differences in total phosphorus concentrations were not statistically significant. Silica concentrations were again higher in the hypolimnion than in the epilimnion.

The heavy metals iron and zinc show no consistent spatial and temporal variations. Zinc is present at concentrations high enough to be potentially toxic to algae.

Organic matter in the harbour was determined as chemical and biochemical oxygen demand and total organic carbon. These parameters are not correlated to one another since different tests measure significantly different substances. Each parameter varies significantly with sampling date. The maximum BOD values were found in June at the time corresponding to the maximum nitrate concentrations. Dissolved organic carbon , however, correlated with BOD, suggesting that this form of organic carbon plays an important role in the oxygen demand of the water column. Most of the industrial, municipal and stormwater outfalls are sources of dissolved organic carbon.

D. SEDIMENT CHEMISTRY

Sediment samples were collected at 25 stations in May and October of 1977 and at 4 stations monthly. There were no significant differences, except for ammonia, seasonally or from 1976 to 1977. The sediments are highly polluted with zinc, lead and chromium and to a lesser extent cadmium and mercury. The highest concentrations are found in deep waters and adjacent to the outfalls. Factor analysis classified the sediments into four main groups: the deep water group, those close to the north shore, those near outfalls and those in the canal region which is influenced by lake-harbour exchange.

E. PHYTOPLANKTON AND BACTERIA

The highest phytoplankton cell densities were observed in the spring with a secondary maximum during the summer. The maximum cell concentrations at any period were found in the upper three to four metres of the water column, which was also the euphotic depth. The community structure was highly dynamic, influenced as it is by the vertically and horizontally unstable physical structure of the water column.

The dominant species throughout most of the year were the Chlorophyta (green algae), the Cryptophyta were the next important group, with Chrysophyta (diatoms) present in small numbers. The bacterial populations were dominated numerically by heterotrophs. These were followed in descending numbers by sulphur oxidizers, nitrifiers, and sulphur reducers. Although processes and reaction rates cannot be accurately assessed from bacterial numbers, the results suggest that organic carbon breakdown and sulphur oxidation are the major sources of the large and sustained water column oxygen demand in the Harbour.

F. 2-DIMENSIONAL NUMERICAL MODEL

The two-dimensional numerical model described in earlier Ministry of Environment publications has been modified to include real-time data for industrial inputs and lake-harbour exchange. Nevertheless, the model simulation is as yet not satisfactory as it does not describe short-term variations at all, and the agreement between observed and models results is better at grid squares removed from meter locations. The major deficiency in this modelling is the use of a two-dimensional model to describe a three-dimensional stratified situation.

The preliminary simulation of total dissolved solids distribution in the harbour was done, and qualitative agreement was obtained, showing high concentrations in the southeastern region and lower concentrations due to lake water intrusions at the canal.

G. 3-DIMENSIONAL NUMERICAL MODEL

The three-dimensional numerical model of hydrodynamics, temperature and water quality as developed by Leendertse et al (1973) has been modified for use in lake systems. The theory of the model is described in detail, with particular reference to the physical parameters for which calibration values must be specified.

Initial calibration runs of the hydrodynamic portion of the model have been performed for Hamilton Harbour using real-time input data. Model performance was assessed by comparing modelled currents to those measured at a harbour location not used as model input. Attempts were made to improve the fit to observed currents by varying the values of the input physical parameters.

Poor model performance was likely the result of vertical instability in the harbour. Water flowing past a current meter which has a fixed vertical position may be representative of different model layers at different times.

The results suggest that any future modelling should involve a larger number of model horizontal layers, as well as vertical strings of current meters for the calibration process.

H. WATER MOVEMENTS

Currents were measured in both 1976 and 1977 in mid-harbour and in the Burlington and Desjardins Canals.

In summer, the mid-harbour currents were to the southerly quadrant for both years. Spectral analyses show diurnal and semi-diurnal periods and the effects of Lake Ontario.

The Burlington Canal flows were uni-directional and towards the Lake in the summer of 1976. During the same period in 1977, the flow was outward in the upper layers but inward below 3.5 metres.

The net exchange for the period from June to November 1976, calculated using the excursion-episode method, varied from 6 to 45 m^3/s representing 0.2% to 1.4% of the harbour volume per day. Net flows calculated from mass balances of conservative substances, assuming a steady-state for a year, are about 35% to 60% of the flows in this report. This discrepancy between the two methods still has to be resolved.

The net flow through the Desjardins Canal varied from 0.6 to 1.5 m^3/s representing 0.02% to 0.05% of the harbour volume per day.

VOLUME II

INPUTS OF MATERIALS TO THE HARBOUR

The inputs of pollutants from tributaries, storm sewers, industrial outfalls and municipal sewage treatment plants to the harbour were obtained under contract by W. J. Snodgrass, McMaster University. The results are given in Volume II of this report. These include estimates of water input from all major watersheds, sewage treatment plants, lake-harbour exchange, rainfall and storm sewers from below the escarpment. The author also points out that exchange flows calculated on the excursion-episode method can lead to unacceptably large theoretical lowerings of the harbour level, as the inflows are not sufficient to balance the outflows.

The estimates of industrial loadings from the two integrated steel mills - Stelco and Dofasco suffer from scarcity of flow and concentration measurements. The major net loadings from Stelco are suspended solids, BOD and iron; from Dofasco, suspended solids, COD, and sulphates. In addition, ammonia, phenols and cyanides are added from both.

The Hamilton sewage treatment plant removes about 80% to 90% of incoming BOD, COD, suspended solids, total phosphorus and iron, but only about 5% to 20% of the nitrogen. The Burlington sewage treatment plant removes 90% of suspended solids, BOD and total phosphorus through chemical precipitation and 70% of total nitrogen (biological removal). The Dundas sewage treatment plant is a large source of phosphorus and ammonia, much of which is removed in Cootes Paradise.

Hamilton has a combined sewer system. The overflows from above the escarpment drain into Redhill and Chedoke Creeks; from below, directly into the harbour. The studies of stormwater inputs are insufficient to give a good estimate of loadings, but those draining directly into the harbour contribute, at the most, 5% of total pollutant load. The author estimates that the municipal sewage treatment plants are the major contributors (greater than 50% of total load) of total phosphorus, soluble phosphorus, total nitrogen, nitrate, total dissolved solids and chloride. Industrial and municipal sources each contribute 30% to 40% of total organic carbon and BOD, whereas industry is a major source of COD, suspended solids and phenols. Streams are significant sources (20% to 25%) only for nitrates, total dissolved solids and chlorides.

The author concludes that improved control of municipal and industrial point sources would produce the most significant improvements in water quality, whereas control on combined sewers would effect only minor improvements.

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VOLUME I

SECTION A

ARTIFICIAL MIXING

SUMMARY

The primary artificial mixing system employed was identical to that of 1976. The system was operational at the beginning of June. At this time, water column dissolved oxygen concentrations were already severely reduced. The theoretically required air flow for maximum column destabilization was not obtained until late July. This flow was sustained for only a few weeks due to subsequent system failures. This year's activity represents the best operational record to date, but it was inadequate from both a theoretical and an observational viewpoint.

Neither vertical thermal structures nor dissolved oxygen concentration could be directly related to aerator activity due to the harbour's naturally vertically diffuse characteristics. The customary recovery in the severely depleted bottom oxygen stock was again seen at the end of July. This recovery may have been due to aerator activity, however a clear cause and effect relationship cannot be established at this time.

Bi-weekly samples of some water column chemical parameters, phytoplankton and bacteria were taken. Despite significant changes in some chemical parameters, such as the elevation of ammonia levels, no direct relationships between water column chemistry and artificial mixing could be established. The same was true for both the phytoplankton and the bacteria measurements. There did, however, appear to be more subtle or indirect effects of artificial mixing on the harbour. Despite higher in situ concentrations of chemical parameters such as ammonia, the assimilative capacity of the harbour did not diminish appreciably. Also, nutrient cycle bacteria appeared to respond to the aerator operation by maintaining and even augmenting their standing stocks.

INTRODUCTION

Water quality studies have been conducted in Hamilton Harbour since 1972. On the basis of the 1972 to 1974 information it was recommended that artificial mixing be instituted as a means for improving the poor water quality which existed. It was anticipated that the aerator system would increase dissolved oxygen concentrations, reduce the levels of heavy metals, nutrients, and dissolved organics, and improve the light penetration. Extensive monitoring and process oriented studies were conducted to examine the impact of aeration on the harbour. These programs have also disclosed in greater detail the physical, chemical and biological processes of the harbour. The monitoring program consisted of a bi-weekly vertical sampling at the four stations (Figure 1) for nutrients, metals, bacteria, phytoplankton, alkalinity, pH, oxygen, chlorophyll and temperature.

In addition to the artificial mixing device operated by the Ministry, a secondary mixing technique developed by Professor M. Baird of McMaster University was examined.

THE MIXING SYTSTEMS

The primary mixing system employed was identical in design to that used in 1975 and 1976, and has been described in detail in the previous reports (MOE, 1977, 1978). The compressor and lines were located off the north face of the Stelco ore dock as in 1976 (Figure 1) however some of the existing lines were replaced.

The operational record is displayed in Figure 2. The 1976 program represents the best performance record to date, with the system functioning from the beginning of June until early September when operations were terminated. The system was completely non-functional for brief periods at the beginning of July and the beginning and end of August. Compressed air flow through the various lines was briefly interrupted over the summer and line #1 was inoperative in the middle of August. As a result of these problems, the average daily flow from the system (Figure 2) was below the critical, theoretical requirement (300 cfm) throughout most of the summer (MOE, 1978). Therefore, it is not surprising that the system could neither promote an oxic environment in the hypolimnion nor a large increase in the dissolved oxygen stocks of the harbour.

The secondary mixing technique employed was that of propelling a series of tori (ring-shaped water masses) downward from a special generator mounted on a raft. The vortex generator consisted of a compressor, a timer, a surge tank and the vortex tank itself which was an open ended cylinder inverted into the water. Pulses of air were released from the surge tank at timed intervals and fed into the vortex chamber which generated ring vortices of water. The vortex of water so generated was 25.4 cm in diameter and displaced approximately 9 m^3/hr of water downwards. Entrainment effects must be added to this estimate and an order of magnitude estimate of transport of aerated water downwards would be 20 m^3/hr. The device was operated for a few hours on several days during July and August in a water column depth of 18 m. Hourly recordings of dissolved oxygen concentration and temperature were taken at depths of 0, 5, 10 and 15 metres.

TEMPERATURE AND DISSOLVED OXYGEN

A definite, harbour-wide surface cooling was noted at the end of July and the beginning of August (Figure 3). This surface cooling was accompanied by a deepening of the thermocline and a slight warming of bottom waters. The phenomena corresponded to that period of peak aerator output (Figure 2) where delivery rates exceeded the theoretical critical flow requirements.

Local surface coolings were observed at all stations periodically throughout the summer and are unlikely to be attributable to aerator operations. Since the harbour exhibits naturally diffuse vertical thermal gradients, periodic changes in the temperature profiles cannot be conclusively related to aerator activity. Large differences in both the absolute temperatures and vertical temperature gradients often existed between stations which further prevented a clear interpretation of the aerator effects. Mixing did not stimulate vertical exchange sufficiently to achieve thermal homogeneity.

The oxygen profiles were likewise unrelated to artificial mixing. The oxygen demand rates were large and exceeded the natural and artifically induced supply rates (refer to Section 'B'). The dissolved oxygen concentrations of the harbour declined rapidly from saturation levels during the spring to bottom anoxia and surface sub-saturation levels during the summer. A slight recovery in both the bottom and surface concentrations was evident near the end of July and the beginning of August. After autumn turnover, which occurred in late September, the vertical oxygen gradient was eliminated. The oxygen concentrations did, however, remain sub-saturated until sometime after survey activity ceased at the end of October (refer to Figures 4 and 5).

The total oxygen stock of the harbour declined rapidly from 3.1 x 10^6 kg of oxygen in April to 0.9 x 10^6 kg of oxygen in early July (Figure 6a, Table 1). The original saturated stock levels were not again attained during the survey period (Figure 6b). Total oxygen stock did, however, show an increase in late summer which corresponded to that period of maximum aerator output. The overall effect of the aerator system on the oxygen stocks was far less than was originally anticipated. This was partly due to late initiation of operation and partly due to the systems inability to deliver compressed air at the required flow rates.

The results of the vortex mixing experiment showed that there was a slow but definite increase in the dissolved oxygen concentrations directly beneath the raft. Vertical mixing was also demonstrated by the temperature profile data. A complete analysis of this experiment, along with a discussion of laboratory experiments and vortex mixing theory can be found in Rohatgi, Baird, and Wairegi (1979).

NUTRIENTS

Filtered reactive phosphorus (FRP) concentrations (as P) ranged from less than 1 ug/L to 96 ug/L. No definite seasonal trend was evident from the survey data. Also, no spatial trends could be found in either the horizontal or vertical dimensions. In general, the FRP concentrations were greater than those of 1976, particularly at stations 4 and 252.

The total phosphorus (TP) concentrations (as P) ranged from 20 to 128 ug/L and, like the FRP, showed no definite trends in space or time. Unlike the 1976 results, no pattern of higher concentrations associated with sediment disturbance was seen. Surface mean concentrations were in general as high or higher than those of the whole water column.

Neither total nor dissolved phosphorus concentrations appeared to be related to aerator activity. Concentrations were not reduced significantly when compared to previous years, despite the significant improvement in aerator operations. This may have been due to the large and continuous loadings of phosphorus to the harbour (refer to Section 'H').

Ammonia concentrations which were approximately uniform with depth, ranged from 0.012 to 6.30 mg/L throughout the year. Concentrations were highest in the spring and rapidly declined until the end of June. Thereafter, concentrations decreased much more slowly. While the seasonal trend resembled those of previous years, it can be seen that the spring concentrations were much higher in 1977 (refer to Section 'C'). The greatest concentrations were found in the eastern end of the harbour, particularly at station 4.

The nitrite concentrations in the harbour ranged from 0.011 - 0.370 mg/L during the sampling period. The lowest concentrations were found in the hypolimnion during the summer. Concentrations changed inversely as the ammonia concentrations during the first part of the year. After the ammonia levels became greatly reduced, no direct relationship could be ascertained between the two parameters.

Nitrate concentrations displayed a great deal more vertical tha.. horizontal variation, in contrast to other nitrogen parameters. The concentrations ranged from 0.20 - 3.37 mg/L over the year with the lowest concentrations being found near the bottom of the harbour. The mean harbour concentrations dropped slightly from early to late spring and then increased to a mid-summer maximum. Although the values remained high throughout the late summer and autumn, they oscillated from one sampling date to the next.

A total Kjeldahl nitrogen, whose concentrations ranged from 0.21 - 7.00 mg/L, showed a seasonal trend similar to ammonia. The concentrations did, however, show a great deal of variation in both the vertical and horizontal dimensions.

While the total nitrogen concentrations were in general greater in 1977 than in 1976, no relationship between either the concentration changes or speciation and artificial mixing could readily be seen.

Silica concentrations, which ranged from 1.10 to less than the detection limit of 0.05 mg/L, were highest in the spring and lowest during the mid-summer period. The dramatic decline in silica, which was observed in late June to early July, coincided with the diatom bloom (refer to Section 'E'). During this period the highest concentrations were observed near the bottom of the harbour. These conditions persisted until Autumn overturn. Therefore, no artificial mixing effects on the concentration or distribution of silica were evident.

ORGANIC CARBON, BOD AND COD

Total organic carbon (TOC) concentrations ranged from 1-16 mg/L. There were no consistent trends in the concentrations with time, station or depth. The lowest values observed occurred on August 10 and these were similar throughout the whole of the harbour. The concentrations, however, had reattained previous levels within two weeks.

Analysis of the total filtered organic carbon (i.e. organic carbon compounds below the 1-2 micron size) showed that it comprised 76-96% on average, of the total organic carbon. Therefore, the changes observed in the total organic carbon concentrations were also seen in the filtered organic carbon concentrations. The mean harbour concentrations observed were similar to those in 1976. None of the changes seen in the organic carbon parameters could be related to aerator activity.

Total inorganic carbon concentrations ranged from 21-29 mg/L, being slightly lower through July and August than in the spring and autumn. The concentrations showed some depth variation throughout the year.

The biochemical oxygen demand (BOD_5) showed no consistent seasonal trend. The BOD's were both horizontally and vertically variable. The values ranged from 1.0 to greater than 8.0 mg/L and in general, the highest values appeared in the epilimnion. The mean values were somewhat higher than those of 1976. BOD_5 values were unrelated to the total organic carbon concentrations.

The chemical oxygen demand (COD) also showed no definite seasonal trend. Its values ranged from 10-150 mg/L and were equally variable horizontally and vertically. In general, the highest values were observed in the epilimnion. The mean harbour values were similar to those observed in 1976 during the spring and early part of the summer. The late summer and autumn values, however, were consistently higher in 1977. The COD showed no direct relationship with either the TOC or the BOD_5.

No direct relationships between artificial mixing and TOC, BOD_5 or COD could be found.

ALKALINITY, PH AND CONDUCTIVITY

The carbonate alkalinity of the harbour decreased gradually from a high of 123 mg/L in the spring to 87 mg/L in the late summer. The harbour waters are therefore well buffered and the pH changes due to primary production or artificial mixing would be minimized. The pH ranged from 7.15-8.60 and was highest in the epilimnetic waters. Values in general, declined from spring to autumn, however, the highest levels were observed in the surface waters in late July and early August which coincided with large increases in the phytoplankton community.

Conductivity ranged from 410-650 u Siemens cm. The mean column values declined throughout the year and the highest values were found in the surface waters.

The values and trends observed for all of the above parameters were consistent with observations made in previous years. No aerator effects were apparent despite improved operations.

TURBIDITY AND SUSPENDED SOLIDS

The turbidity levels in the harbour ranged from 1.5 to 7.5 Formazin units which were somewhat greater than the 1.5-2.3 (Formazin units) range of 1976. Turbidity levels were in general, greatest in the epilimnion. There was a good deal of variation in turbidity between stations and with depth. The stations at the extreme end of the harbour, 270 and 4 (refer to Figure 1), had the highest turbidity levels. Values were greatest at all stations in the late spring and early summer, however no definite relationship between artificial mixing and turbidity was found.

The suspended solids ranged from 2-14 mg/L over the year. The highest values occurred in the epilimnion but in general, showed both spatial and temporal variability. The average harbour values were bimodally distributed, with peaks in early May and late July.

Turbidity and suspended solids were linearly correlated,

Turbidity = 0.34 (suspended solids) - 1.10;

At the 0.001 level with r = 0.80. This relationship shows that when turbidity is 0, the suspended solids content of the harbour is 1.10 mg/L. This value was similar to that found in 1976 (1.78 mg/L) and suggests that particles less than 2 microns were abundant. These particles have a forward scattering effect on penetrating light and are therefore not measured as turbidity.

The slope of the regression line (0.34) was significantly different from that obtained in 1976 (0.97). The reason for this change in slope, which implies that turbidity values increased much more slowly with increased suspended solids concentrations in 1977 than in 1976, is not known.

HEAVY METALS

Iron and zinc, which had been identified as major environmental concerns in previous years, were monitored bi-weekly at the four stations.

Iron concentrations ranged from 0.04-1.3 mg/L. The values were in general greater at station 4 than other stations and were in excess of the IJC guidelines of 0.30 mg/L throughout the harbour. No definite seasonal or vertical trend was apparent in the data.

Zinc was again present in high concentrations with a range of 0.02-0.46 mg/L. Although the values were spatially and temporally variable, the average column concentrations normally exceeded the IJC objective of 0.03 mg/L. No effects of artificial mixing on either the zinc or iron concentrations were apparent.

Other metals such as manganese, copper and mercury were sampled too infrequently to relate them to aerator activity.

A more detailed analysis and discussion of the chemical water quality can be found in Section C of this report.

BIOLOGICAL RESPONSES

BACTERIAL POPULATIONS

Bi-weekly samples were taken for fecal coliforms, heterotrophs, sulphur cycle and nitrogen cycle bacteria from stations 4, 258 and 270 at the surface, mid-depth and bottom. Similar samples were also taken from the surface and bottom at station 252.

The fecal coliform population densities, which indicate domestic sewage contamination, showed a slight increase over the 1976 levels. The highest concentrations were observed at station 4. The population densities were highly variable in space and time which precluded a clear linkage of population size and distribution with aerator activity. Fecal coliform levels in the surface water frequently exceeded the 100 counts per 100 ml level which is the upper limit permissible for body contact recreation.

Heterotroph population densities showed a significant increase over the previous year at all stations. This trend of increase in population densities, which has been observed since 1975, may be due to aerator activity, however, changes in the population densities observed within a single year cannot be directly linked to aerator activity. The highest levels of heterotrophs were generally found at station 4 (refer to Table 1).

Both the sulphur oxidizers and sulphur reducers showed notable declines in population size. This may have been due to the decline in sulphur, particularly reduced sulphur, concentrations observed in the sediments in 1976. Sulphur oxidizer levels were greatest at station 4, while the sulphur reducer levels were greatest at station 252 (refer to Table 1). A good deal of spatial and temporal variability was seen in both populations and no direct effect of aerator activity could be shown.

The nitrogen cycle bacteria had shown a dramatic increase in population densities since 1976. This large increase was probably due to aerator activity. The greatest increase during the year centred around peak aerator operation. This increase was most likely a result of artificial mixing since the ammonia levels were coincidentally at their lowest levels for the year.

PHYTOPLANKTON

Phytoplankton samples were collected weekly at station 258 from the beginning of May until the middle of October. Samples were also collected for chlorophyll a analysis, which is used as an indicator of algal abundance, however, due to analytical difficulties the results cannot be used. The phytoplankton numbers demonstrated a large amount of vertical variability from week to week, but neither total algal abundance nor vertical arrangement, nor species composition could be directly related to aerator activity.

ZOOPLANKTON

Zooplankton were monitored, as well as surface phytoplankton throughout the harbour and primary productivity was measured by McMaster University. The results of this program are discussed in Harris, Piccinin, Haffner, Snodgrass and Polak (1979).

OTHERS

Bottom fauna were collected at various times during the year by the West Central Region (MOE), however, analysis is as yet incomplete.

Various fish species were examined for organochlorine contaminants during the year and the results of these findings are available from the Ontario Ministry of the Environment, Water Resources Branch.

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Table 1: Bacterial Populations of Hamilton Harbour - 1977 (Annual Geometric Means), Counts/100 mL

	Surface	Middle	Bottom
	Station #4		
Fecal Coliforms	179	88	35
Heterotrophs	26,228,500	7,783,400	6,709,700
Sulphur Oxidizers	1,947,745	704,252	117,728
Sulphur Reducers	217	25	66
Nitrosomonas	6,348	3,950	5,247
Nitrobacter	2,467	2,780	5,041
	Station #252		
Fecal Coliforms	48	-	96
Heterotrophs	14,803,900	-	14,984,100
Sulphur Oxidizers	315,899	-	86,341
Sulphur Reducers	212	-	274
Nitrosomonas	4,051	-	8,919
Nitrobacter	3,100		8,028
	Station #258		
Fecal Coliforms	68	31	18
Heterotrophs	10,736,600	4,905,800	4,110,600
Sulphur Oxidizers	204,853	73,206	151,287
Sulphur Reducers	26	18	19
Nitrosomonas	3,400	10,638	21,175
Nitrobacter	5,636	5,462	4,720
	Station #270		
Fecal Coliforms	49	61	22
Heterotrophs	8,665,000	5,300,500	5,122,900
Sulphur Oxidizers	29,351	40,554	456
Sulphur Reducers	47	24	16
Nitrosomonas	2,700	4,052	21,500
Nitrobacter	6,608	5,003	18,473

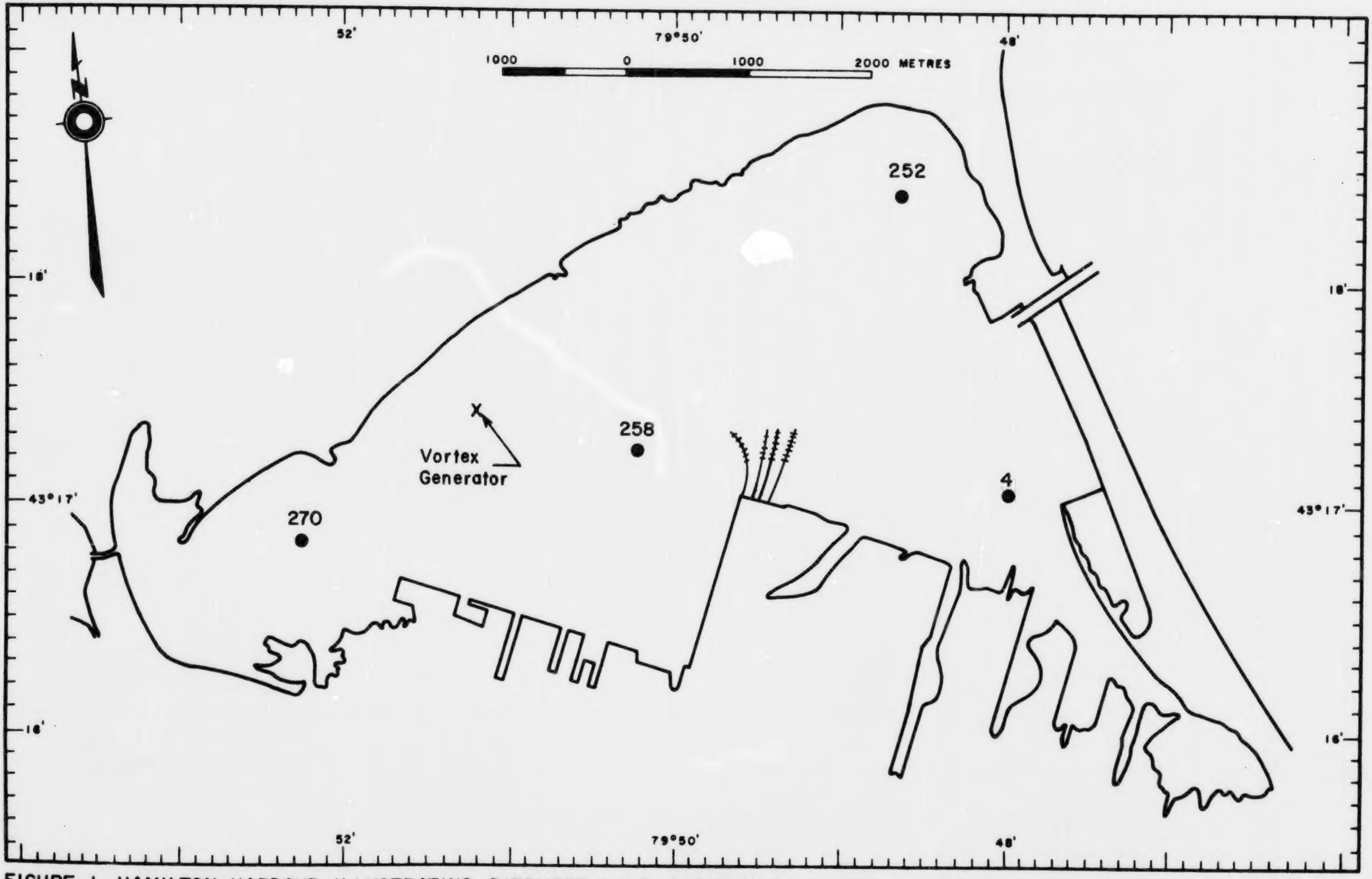
52'
79°50'
48'
1000
0
1000
2000 METRES
18'
43°17'
16'
252
258
270
4
Vortex Generator

FIGURE I HAMILTON HARBOUR ILLUSTRATING DIFFUSER LINE, POSITION OF VORTEX GENERATOR AND MAJOR SAMPLING STATIONS

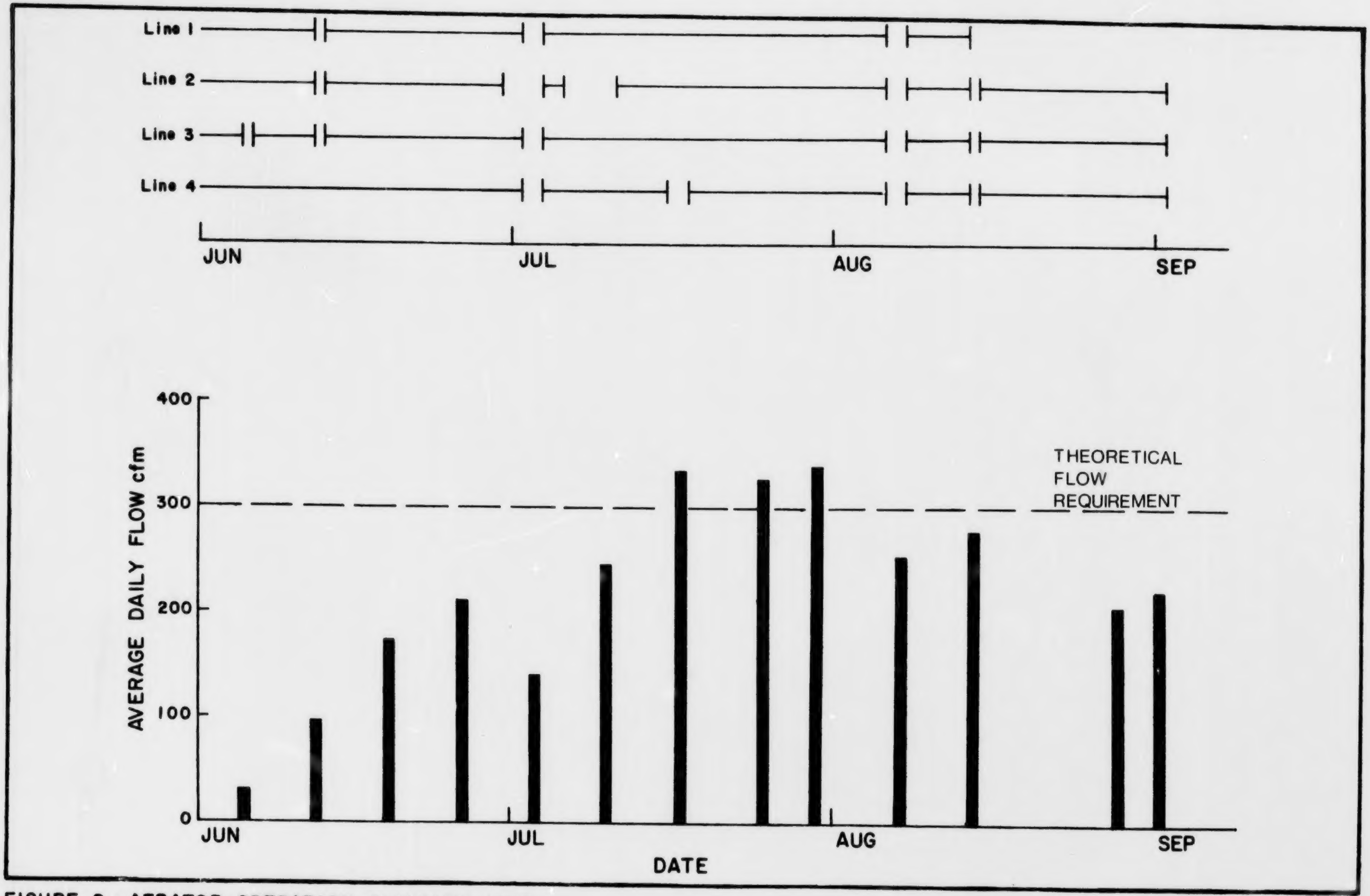

FIGURE 2 : AERATOR OPERATION SUMMARY 1977

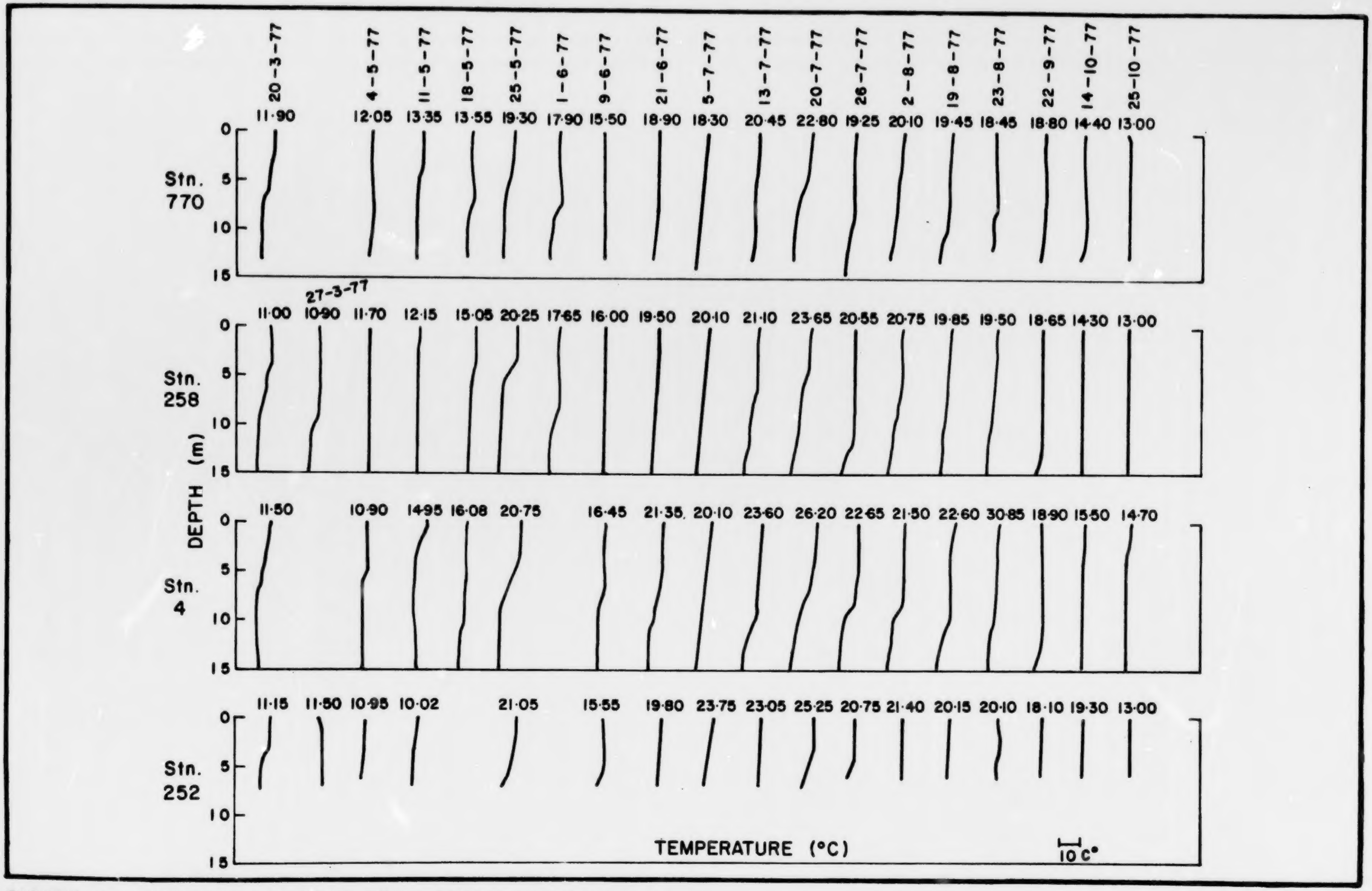

FIGURE 3 : HAMILTON HARBOUR TEMPERATURE PROFILES 1977.

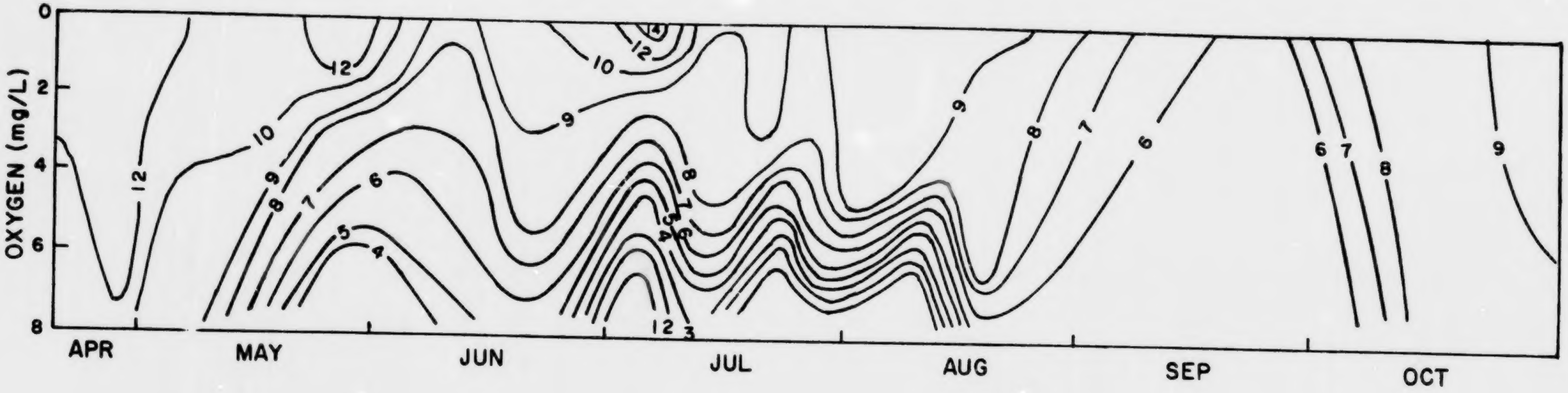

FIGURE 4a : DISSOLVED OXYGEN PROFILES (mg/L) HAMILTON HARBOUR 1977, STATION 252 .

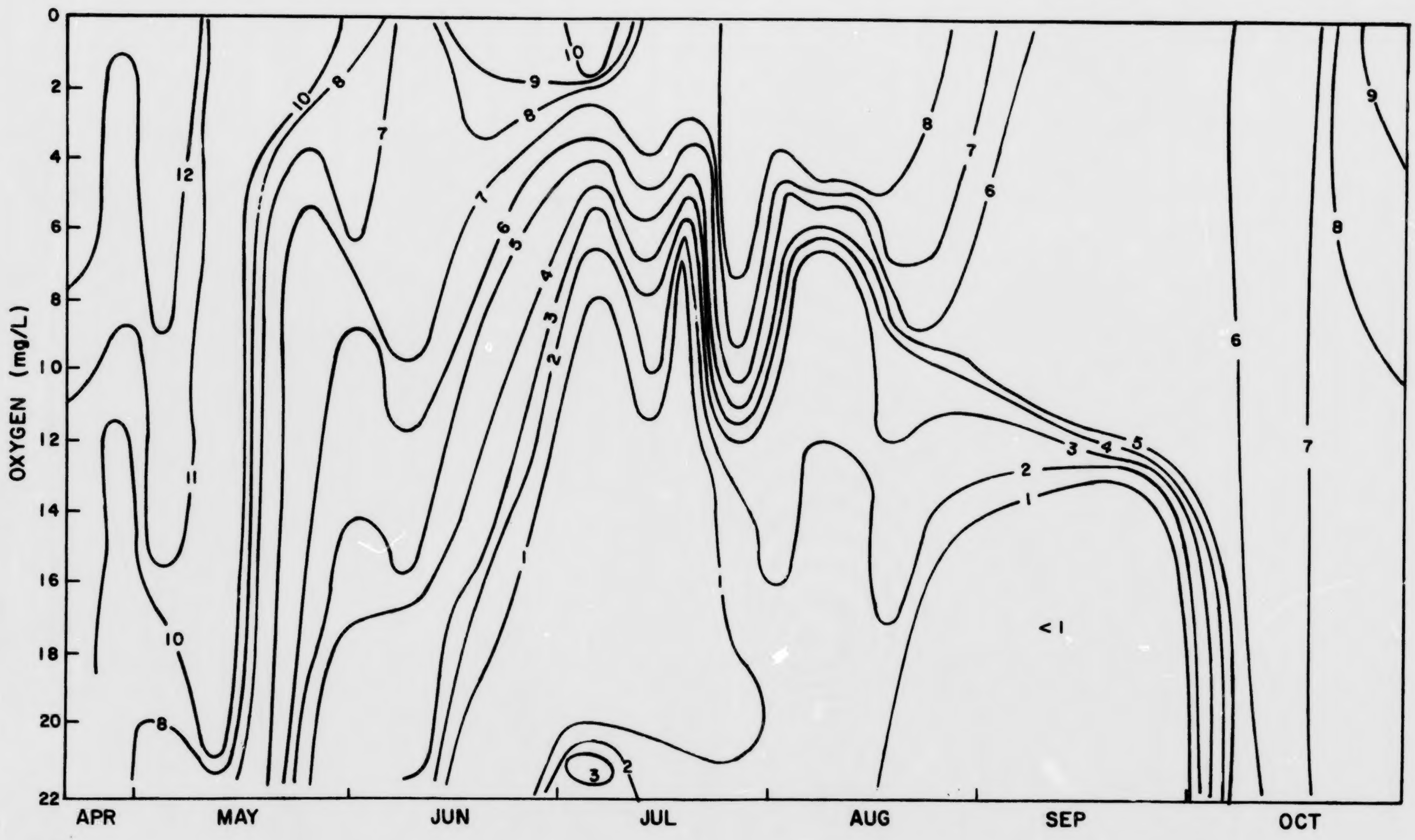

FIGURE 4b : DISSOLVED OXYGEN PROFILES (mg/L) HAMILTON HARBOUR 1977, STATION 258

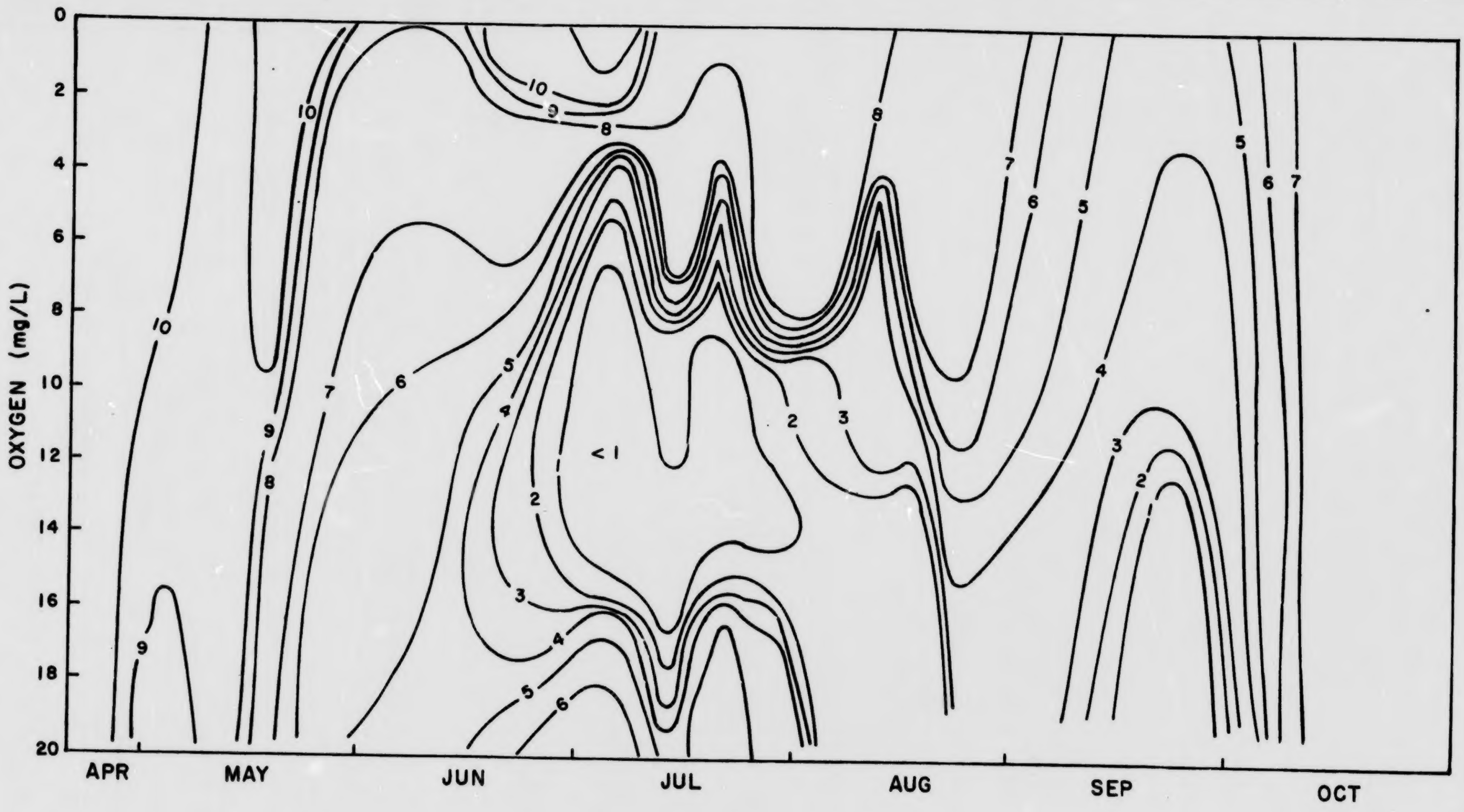

FIGURE 5a: DISSOLVED OXYGEN PROFILES (mg/L) HAMILTON HARBOUR, STATION 4.

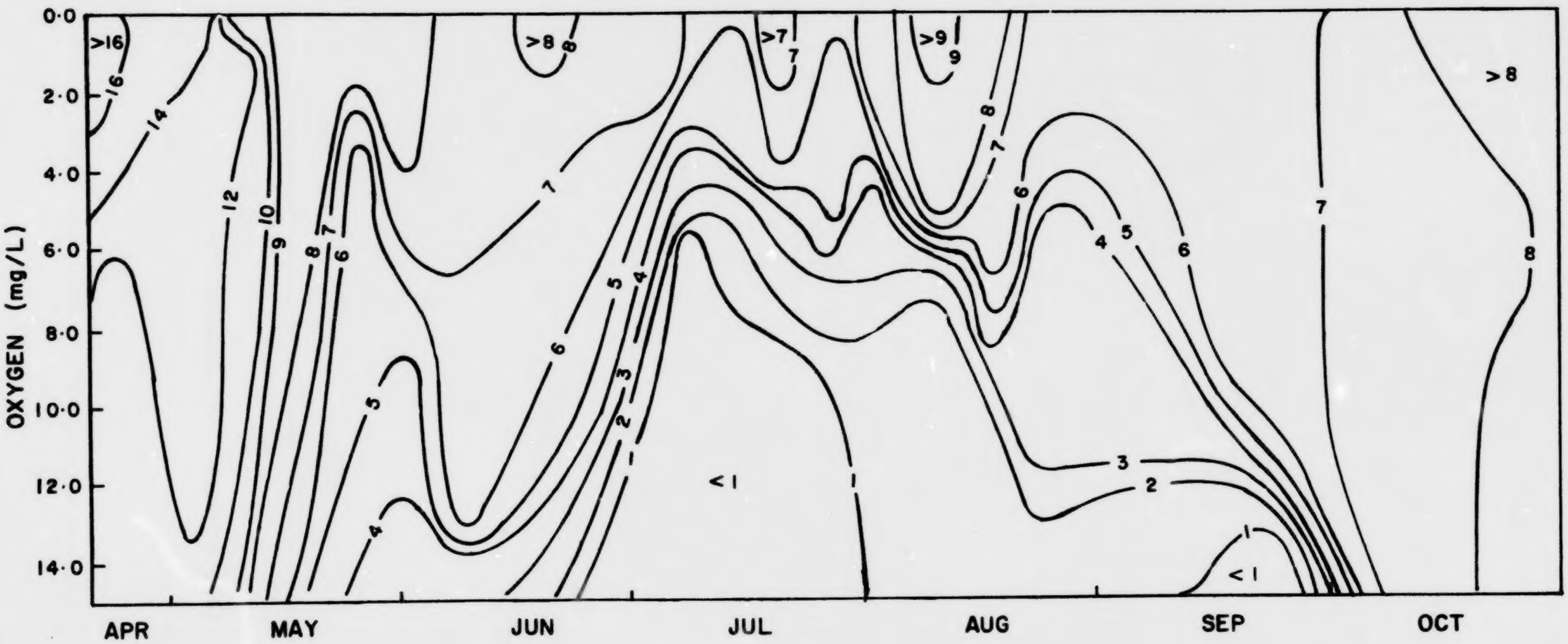

FIGURE 5b : DISSOLVED OXYGEN PROFILES (mg/L) HAMILTON HARBOUR 1977, STATION 270.

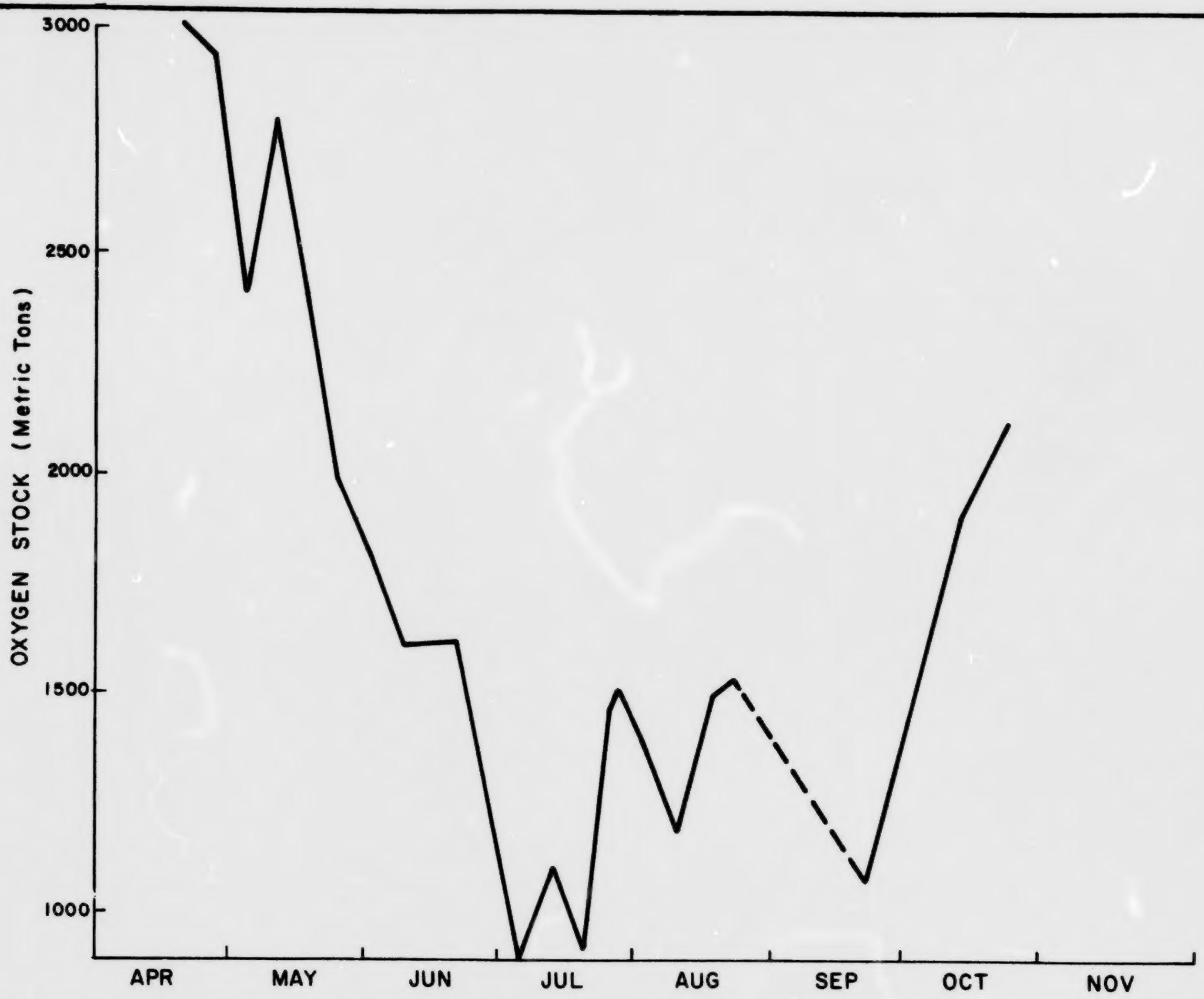

FIGURE 6a: DISSOLVED OXYGEN STOCK HAMILTON HARBOUR, 1977.

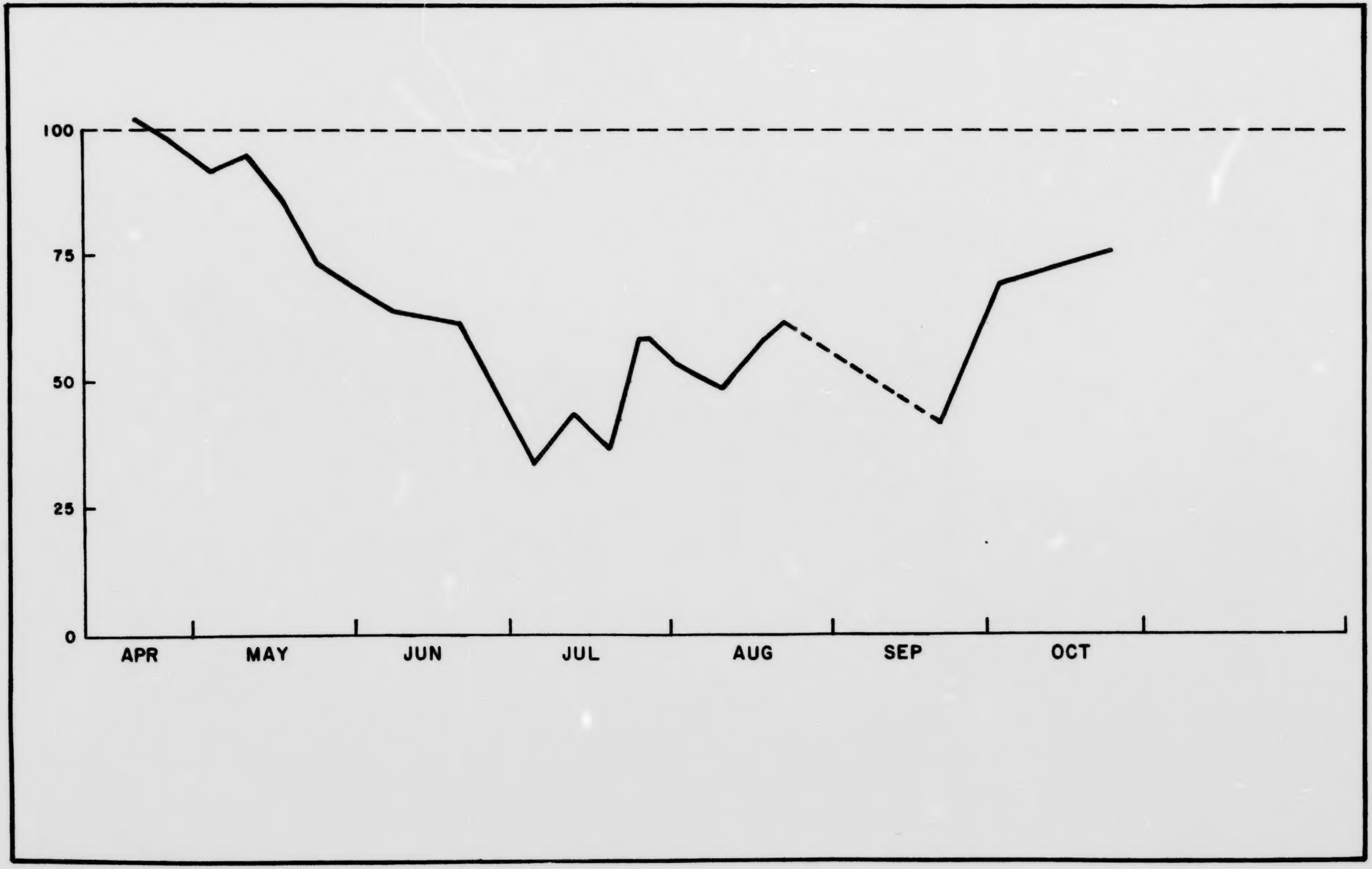

FIGURE 6b : OXYGEN STOCK AS % OF SATURATION STOCK .

HAMILTON HARBOUR STUDY

1977

VOLUME I

SECTION B

OXYGEN BUDGET

SUMMARY

The average oxygen stocks in the Harbour were the same as in previous years, reaching a minimum in early July when the epilimnion was also undersaturated. The lenses of oxygen-rich water in the hypolimnion during June and July are, in all likelihood, lake water entering via the Burlington Canal.

The vertical turbulent fluxes of oxygen were calculated for different seasons using a model which divides the Harbour vertically into layers of equal thickness. The layers are considered as horizontally homogeneous. The vertical diffusion coefficient, D, was calculated from the fluxes and the known oxygen gradients. A very pronounced minimum in D was found at the thermocline, but, because of the high oxygen gradients, the oxygen flux was still considerable and at no time during the summer was the hypolimnion effectively isolated from the epilimnion.

A simple single box predictive model for oxygen concentrations was developed, using sediment oxygen demand and water column oxygen demand as sinks and reaeration, photosynthesis and lake-harbour exchange as sources. Quite good agreement between predicted and observed mean oxygen concentrations was achieved. The model suggests that to reach an oxygen concentration of 5 mg/L, which is the Ontario objective for the protection of warm-water biota, the water column demand should be reduced by 20%.

INTRODUCTION

A rather extensive study of oxygen conditions in Hamilton Harbour was conducted in 1976 and was published in the 1976 Hamilton Harbour Report(MOE, 1978). In 1977, weekly oxygen vertical profiles were collected at the four main sampling stations (Figure 1). This section summarizes some of the findings of the oxygen budget of the harbour in 1977 and shows some of the new techniques applied to the data.

HAMILTON HARBOUR DISSOLVED OXYGEN STOCKS

The oxygen profiles measured weekly in 1977 were used to calculate oxygen contents of the harbour by the same method as described in the 1976 report. The total amount of oxygen dissolved in the harbour waters is given in Figure 2. The thick line in this figure indicates the 1977 dissolved oxygen stocks. As can been seen, the seasonal changes of the 1977 stocks are similar to those of the previous years. The minimum in 1977 was reached in early July, which is later than in 1976 but earlier than in 1975. The minimum oxygen content of the harbour is somewhat higher than in the previous years but the difference is not substantial. Following the July minimum, the DO stock increased slowly until the end of August, and again decreased to a secondary minimum in mid-September. This secondary minimum could be related to oxygen depletion occurring after the cessation of artificial mixing, but before the commencement of natural overturn. The late summer decrease seems to be a regular pattern as it was also observed in 1975 and 1976.

Figure 3 shows the average 1977 oxygen concentrations in the epilimnion (0 to 3 m from surface) and hypolimnion layers (7 m - bottom). The average hypolimnion concentration was below 5 mg L^{-1} between the middle of June and the end of September. The Ontario objective for the protection of warm-water biota is 5 mg L^{-1} when the temperature is between 10 and 15°C. The average epilimnion concentration was always greater than 5 mg L^{-1}, reaching a minimum slightly below 6 mg L^{-1} near the end of September. The epilimnion is, however, below saturation from the end of May to the middle of October.

VERTICAL EXCHANGE

A simple model of vertical oxygen exchange can be built using previously obtained information on sediment and water column oxygen demands. The vertical turbulent exchanges can then be calculated from the model results.

The water reservoir is divided into a finite number of layers of equal thickness (Figure 4). Any particular layer i has a volume V_i and upper and lower boundaries of area A_{i+1} and A_i, respectively, because of the slope of the basin. The area of sediment exposed in the layer is S_i and $A_{i+1} = A_i+S_i$, except for the bottom layer where $A_1=S_1=A_2$. The oxygen concentration is uniform in each layer and equal to C_i.

In this model all oxygen in the layer i is assumed to enter by vertical exchange from layer i+1 (flux r_{i+1}). Oxygen is being lost by a) vertical transfer to the lower layer i-1 (flux r_i), b) by water column oxygen demand (WCOD) and c) by sediment oxygen demand (SOD).

Thus, the change in the dissolved oxygen stock in layer i (ΔM_i) between two dates t_1 and t_2 is

$$\Delta M_i = R_{i+1} - R_i - SOD_i - WCOD_i \qquad (1)$$

where R_{i+1} = rate of oxygen input from layer i+1

R_i = rate of oxygen loss to layer i-1

For input from layer i+1

$$R_{i+1} = A_{i+1} \int_{t_1}^{t_2} r_{i+1} \, dt$$

where r_{i+1} is the flux

Assuming that r_{i+1} is constant between the two dates.

$$R_{i+1} = A_{i+1} \, r_{i+1} \, (t_2 - t_1) \qquad (2)$$

Loss of oxygen to the lower layer can be expressed similarly as

$$R_i = A_i \, r_i \, (t_2 - t_1) \qquad (3)$$

Amount of oxygen used by sediments

$$SOD_i = S_i \int_{t_1}^{t_2} k_s \, dt \qquad (4)$$

Sediment oxygen demand k_s in Hamilton Harbour can be approximated (Polak and Haffner, 1978) by equation

$$k_s = 0.72 + 0.26c \quad (g \; O_2 \; m^{-2} d^{-1}) \qquad (5)$$

where c is the oxygen concentration at time t.

Assuming linear change of oxygen concentration between the dates t_1 and t_2

$$c = ((t - t_1)/(t_2 - t_1)) \, (c_2 - c_1) + c_1 \qquad (6)$$

Substituting (5) and (6) into (4)

$$SOD = S_i \int_{t_1}^{t_2} \Big\{0.72 - 0.26\ t_1\ (c_2 - c_1)/(t_2 - t_1) +$$

$$0.26\ c_1 + 0.26\ t\ (c_2 - c_1)/(t_2 - t_1)\Big\}\ dt$$

or after integration and rearrangement

$$SOD_i = S_i(t_2 - t_1)\ (0.72 + 0.13\ (c_1 + c_2)) \qquad (7)$$

Similarly, using the equation for water column oxygen demand in Hamilton Harbour (Polak and Haffner, 1978)

$$k_w = 0.24 + 0.07c \quad (g\ O_2\ m^{-3}\ d^{-1}) \qquad (8)$$

the total oxygen used in the water of layer i is

$$WCOD_i = V_i(t_2-t_1)\ (0.24+0.035(c_i+c_2)) \qquad (9)$$

Combining (1), (2), (3), (7) and (9)

$$\begin{aligned} \Delta M_i = {} & (t_2 - t_1)\ (A_{i+1}\ r_{i+1} - A_i\ r_i) \\ & - S_i\ (t_2 - t_1)\ (0.72 + 0.13(c_1 + c_2)) \\ & - V_i\ (t_2 - t_1)\ (0.24 + 0.035(c_1 + c_2)) \end{aligned} \qquad (10)$$

From this equation, the vertical turbulent fluxes r_i and r_{i+1} can be calculated since they are the only unknowns, using the following procedure.

For the bottom layer, there is no turbulent exchange downwards and r_1 and R_1 therefore equal zero. From eq. (1),

$$R_2 = \Delta M_1 + SOD_1 + WCOD_1 \qquad (11)$$

or, expressed in terms of eq. (10),

$$\begin{aligned} r_2 = \Big\{ & \Delta M_1 + S_i(t_2-t_1)(0.72+0.13(c_1+c_2)) \\ & + V_1(t_2-t_1)(0.24+0.035\ (c_1+c_2))\Big\}/A_2(t_2-t_1) \end{aligned} \qquad (12)$$

Knowing now r_2 and R_2, R_3 and r_3 can be calculated from

$$R_3 = \Delta M_2 + R_2 + SOD_2 + WCOD_2 \qquad (13)$$

By iterating this process for the remaining layers, all the other r terms can be calculated.

The vertical oxygen fluxes for different periods in 1976 were calculated (Fig. 5). In April, the fluxes were as high as 16g O_2 $m^{-2}d^{-1}$ at the surface and 6.5 at 18 m. The fluxes decreased considerably to between 6.3 and 1.1 by June 20. The averaged fluxes for the whole field season (April 18-October 27) and the stratified period (June 11-September 16) are also shown.

The flux is a function of both the oxygen gradients and the coefficient of eddy diffusion D (in $cm^2 s^{-1}$) and can be expressed by

$$F = 8.64 \, D \frac{dc}{dx} \tag{14}$$

where F is the oxygen flux through a unit area in $gm^{-2}d^{-1}$, c is the oxygen concentration in mg L^{-1}, x is the distance in metres and 8.64 a conversion factor.

Coefficients D calculated from average oxygen fluxes and oxygen gradients for stratified periods of 1975 (June 17 to September 16), 1976 (June 11 to September 16) and 1977 (June 9 to September 22) are shown in Figure 6 along with average depth profiles of temperature and dissolved oxygen concentrations for the stratified period of 1976. The eddy diffusion coefficients displayed a marked minimum near the thermocline. This indicates that the turbulent exchange is at a minimum in this layer. However, oxygen flow through the thermocline was still considerable because of the steep oxygen gradients (Figure 5) and at no time during the year was the hypolimnion effectively isolated from the epilimnion. The vertical exchange along with the water column oxygen demand explains why even the epilimnetic waters were undersaturated for prolonged periods of time in the summer. The only occasions in which the mean dissolved oxygen concentrations exceeded saturation were at times when rapid heating was taking place. This effectively formed a more stable water column during this period, cutting off exchange between the epilimnion and hypolimnion. The occasions on which the dissolved oxygen depletion in the surface layer was most severe coincided with periods of higher vertical exchange, early in the season during the partial overturn in June and late in the season during fall overturn.

During all three years, lenses of oxygen rich water were observed in the otherwise anoxic hypolimnetic waters of the harbour. Figure 6 shows a marked local maximum at depths of 16 to 17 m. The lens of oxygen-rich water was most evident at station 4 during late June and July 1977. It is believed that these lenses represent a portion of oxygen-rich waters from Lake Ontario entering the harbour through the Burlington ship canal.

PREDICTIVE MODEL

Some of the results and equations developed previously for the SOD and WCOD in Hamilton Harbour (MOE, 1978; Polak and Haffner 1978) can be combined into a simple one layer box model capable of predicting how different water quality abatement measures could affect the oxygen situation of the harbour.

If on one date the oxygen stock in the harbour is OS1, then at some date n days later the stock OS2 will be given by

$$OS2=OS1+R+LH+PHOT-WCOD-SOD \tag{15}$$

with the individual terms described and estimated below.

Assuming that the harbour volume V does not change between those two dates we can write

$$OS1 = c_1V \qquad (g\ O_2) \tag{16}$$

$$OS2 = c_2V \qquad (g\ O_2) \tag{17}$$

where c_1 and c_2 are the average oxygen concentrations in mg L^{-1} at the two dates.

The amount of oxygen used by the water column between the two dates (WCOD) can be estimated using the equation

$$WCOD = nV(0.24 + 0.07\ (c_1 + c_2)/2) \qquad (g\ O_2) \tag{18}$$

The sediment will consume

$$SOD = nA\ (0.72 + 0.26\ (c_1 + c_2)/2) \qquad (g\ O_2) \tag{19}$$

Here A is the area of the harbour in m^2 and V is the volume of the harbour in m^3.

The aeration rate for the early season was estimated (Polak and Haffner 1978) at 9.0 g O_2 m^{-2} d^{-1} and therefore the oxygen supplied by aeration (R) is

$$R = 9nA \qquad (g\ O_2) \tag{20}$$

The lake-harbour net oxygen exchange (LH) at 1% of the harbour volume per day can be estimated by the equation

$$LH = 0.01nV(12-(c_1+c_2)/2) \qquad (g\ O_2) \tag{21}$$

assuming that the average lake water oxygen concentration for the period was 12 mg L^{-1}. Photosynthesis (PHOT) was estimated (Polak and Haffner, 1978) to be 1.0 g O_2 m^{-2} d^{-1}. Its contribution is

$$PHOT=nA \qquad (g\ O_2) \tag{22}$$

The extent of reduction in the WCOD can be expressed by (100-x)/100 where x is the percent reduction of the present WCOD. Thus x = 0 fixes the WCOD at the present level and x = 100 means complete elimination of the WCOD. Introducing equations (16) to (22) into (15) and rearranging results in

$$c_2 = \left[n\left\{9.28A+V\left[0.12-0.24(100-x)/100\right]\right\}+c_1\left\{V-nV(0.005+0.035(100-x)/100)-0.13nA\right\} \middle/ \left\{V+n(0.005V+0.13A+0.035V(100-x)/100)\right\} \right] \tag{23}$$

As an example of the use of this equation, concentrations for April 23rd to June 18, 1976 were calculated using different values of x (Fig. 7). With no reduction in WCOD (x=0), the calculated average harbour dissolved oxygen concentration on June 19, 1976 was 2.6 mg L^{-1}. This is in close agreement with the average of 2.4 mg L^{-1} based on survey data. By reducing the WCOD by 20 percent, the calculated average oxygen concentration was 5.2 mg L^{-1}. To reach an average concentration of 9.6 mg L^{-1} of oxygen, which is the saturated dissolved oxygen concentration at the harbour average temperature, the WCOD must be decreased by 46 percent of the 1976 value.

In interpreting Figure 7 it has to be borne in mind that the calculated values are only estimates because of all of the approximations used during development of equation (23). One of the most serious approximations is that the atmospheric reaeration, which is the main source of the oxygen to the harbour, remains constant. In reality, the extent of reaeration decreases with increasing surface water DO, and is also dependent upon the wind velocity. Thus the actual decrease would probably be represented more closely by a curve located below the one shown in Figure 7, and higher reductions in WCOD would be required to retain complete saturation. The model assumes a one layer system while during the stratification period two layers are formed and oxygen depletion in the hypolimnion is speeded up by its partial separation from the oxygen-rich epilimnion.

RELATIONSHIP OF SEDIMENT OXYGEN DEMAND TO OXYGEN CONCENTRATION AND TEMPERATURE

It was shown (MOE, 1978) that sediment oxygen demand as measured in the laboratory depends on the temperature and on the oxygen concentrations in the overlying water. The dependence was given in a graphical form. It would be more convenient, however, to have a general mathematical function which will express this relationship. This would allow the use of a single measurement of the sediment oxygen demand (preferably measured in situ) to determine values for a wider concentration and temperature range. A simple mathematical expression for this dependence can be derived as follows.

Assuming that the sediment oxygen demand is only a function of oxygen concentration c and temperature t we can write

$$k_s = k_s(c,t) \tag{24}$$

by differentiation

$$dk_s = \left(\frac{\partial k_s}{\partial c_t}\right)_t dc + \left(\frac{\partial k_s}{\partial t}\right)_c dt \tag{25}$$

The problem is to find the partial differentials $(\partial k_s/\partial c)t$ and $(\partial k_s/\partial t)_c$. It was shown in the 1976 report that the dependence of the sediment oxygen demand on oxygen concentration in the overlying water at constant temperature can be expressed by the equation

$$k_s = ac^b \tag{26}$$

This equation was shown to be valid for diffusion accompanied by a chemical reaction (Edwards and Rolley, 1965).

Equations expressing the dependence of the sediment oxygen demand on temperature at constant oxygen concentration have been suggested previously. Hargrave (1969) used an equation similar to equation (26). Generally, a classical Arrhenius type relationship can be used for the dependence of the reaction rates of both chemical and biological reactions on temperature. This can be written for k_s as

$$k_s = Re^{-S/T} \tag{27}$$

where R, S are constants, and T is the temperature in degrees K.

Equations (22) and (23) can be used to express the partial differentials in equation (21).

Assuming that a and b are independent of oxygen concentration, then from equation (26)

$$(\partial k_s/\partial c)_t = b(k_s/c) \tag{28}$$

Similarly from equation (27) assuming R and S are independent of temperature

$$(\partial k_s/\partial t)_c = Sk_s/T^2 \tag{29}$$

Introducing (28) and (29) into (25) we get

$$dk_s = b(k_s/c)dc+S(k_s/T^2)dt$$

which gives after integration

$$k_s = Q\ c^be^{-S/T} \tag{30}$$

Equation (30) was used for correlation of the 1976 experimental laboratory data. Since it is nonlinear for parameters Q, b and S, the Newton-Raphson method with the least-square fit of the increments was used to evaluate their numerical values. For the 1976 laboratory data the final equation is

$$k_s = 2.53 \times 10^7\ c^{0.346}e^{-4989/T} \tag{31}$$

where k_s is in g O_2 $m^{-2}d^{-1}$, c is in mg L^{-1} and T is in degrees K.

Equation (30) can be used to calculate the sediment oxygen demand at different temperatures and concentrations. Thus, $k_s(t_2,c_2)$ can be calculated from $k_s(t_1,c_1)$ using:

$$k_s(t_2,c_2) = k_s(t_1,c_1)(c_2/c_1)^b \exp\left\{S(1/T_1-1/T_2)\right\} \tag{32}$$

if b and S are known.

During derivation of equation (30) some approximations were used. These include independence of coefficient b on concentration and coefficient S on temperature. As this is strictly not true, equation (30) is valid only for limited temperature and concentration intervals. Also, coefficients given in equation (31) were calculated for one type of sediment only and specific laboratory conditions. For different sediment and/or experimental conditions the coefficients will have different values.

It was not possible to calculate the coefficients of equation (30) from the 1976 Hamilton Harbour field data, as the temperature varied very little from survey to survey. Data of Edwards and Rolley (1965) were fitted successfully. For the two different sediment types given in their paper, values of b were 0.432 and 0.383 while S had values of 6488 and 7288, respectively. There was much larger variation in the value of Q. Variations in b and S were not too large considering that sediments were from different locations and origins (river mud affected by pollution), and agree well with the constants of equation (31). Thus, even though the absolute value of the sediment oxygen demand is different, the temperature and concentration dependence is similar and equation (32) can be used for interpolation with average b of 0.39 and S of 6250. Equation (32) can be rewritten in the form

$$k_s(t_2,c_2) = k_s(t_1,c_1)(c_2/c_1)^{0.39} \exp\left\{6250(1/T_1-1/T_2)\right\} \tag{33}$$

This general equation is believed to be suitable for temperature and concentration transformation of SOD data for sediments affected by pollution.

CONCLUSIONS

1. The average oxygen concentration in the hypolimnion of Hamilton Harbour was below the provincial objective of 5 mg L^{-1} between the middle of June and the end of September, 1977. This objectives is designed for the protection of aquatic biota when the temperature is between 10° and 15°C. The average epilimnion concentration was always greater than 5 mg L^{-1}, reaching a minimum slightly below 6 mg L^{-1} near the end of September. The epilimnion is, however, below saturation from the end of May to the middle of October.

2. A greater simplified one-box model of the oxygen concentrations in the Harbour predicts that, to achieve average oxygen concentration greater than 5 mg L^{-1}, the total water column oxygen demand should be reduced by around 20%. The relationships between the water column oxygen demand and the biochemical processes in the Harbor and between the demand and the loadings to the Harbor from industry, municipal sewage treatment plants and stormwater runoff have to be determined before definite recommendations for water quality management can be made.

3. A very pronounced minimum in the calculated D, the vertical diffusion coefficient, was found at the thermocline. Because of the high oxygen gradients, the oxygen flux was still considerable and at no time during the summer was the hypolimnion effectively isolated from the epilimnion.

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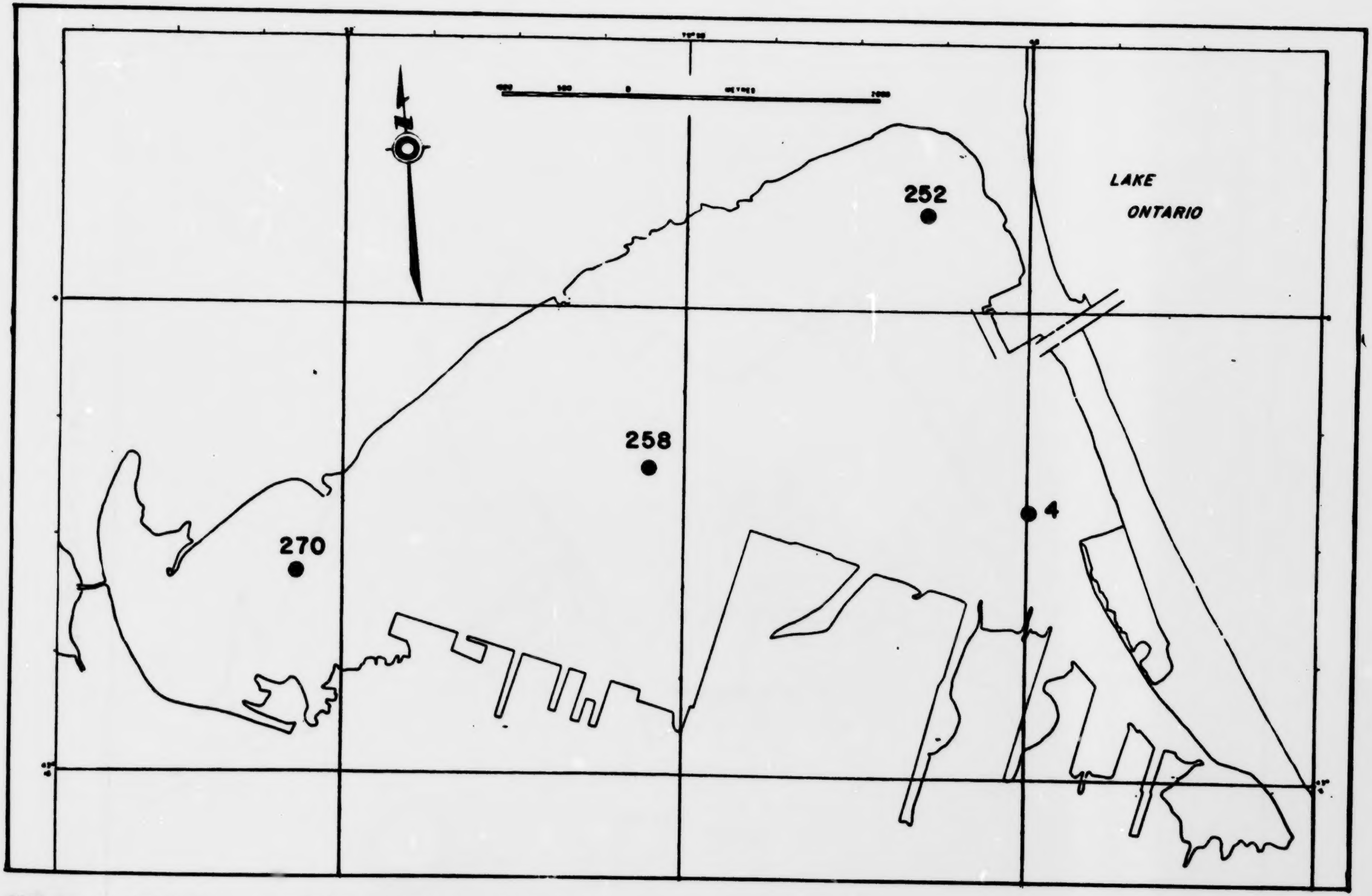

N
500
0
METRES
2000
LAKE
ONTARIO
252
258
270
4

FIGURE I HAMILTON HARBOUR SAMPLING GRID.

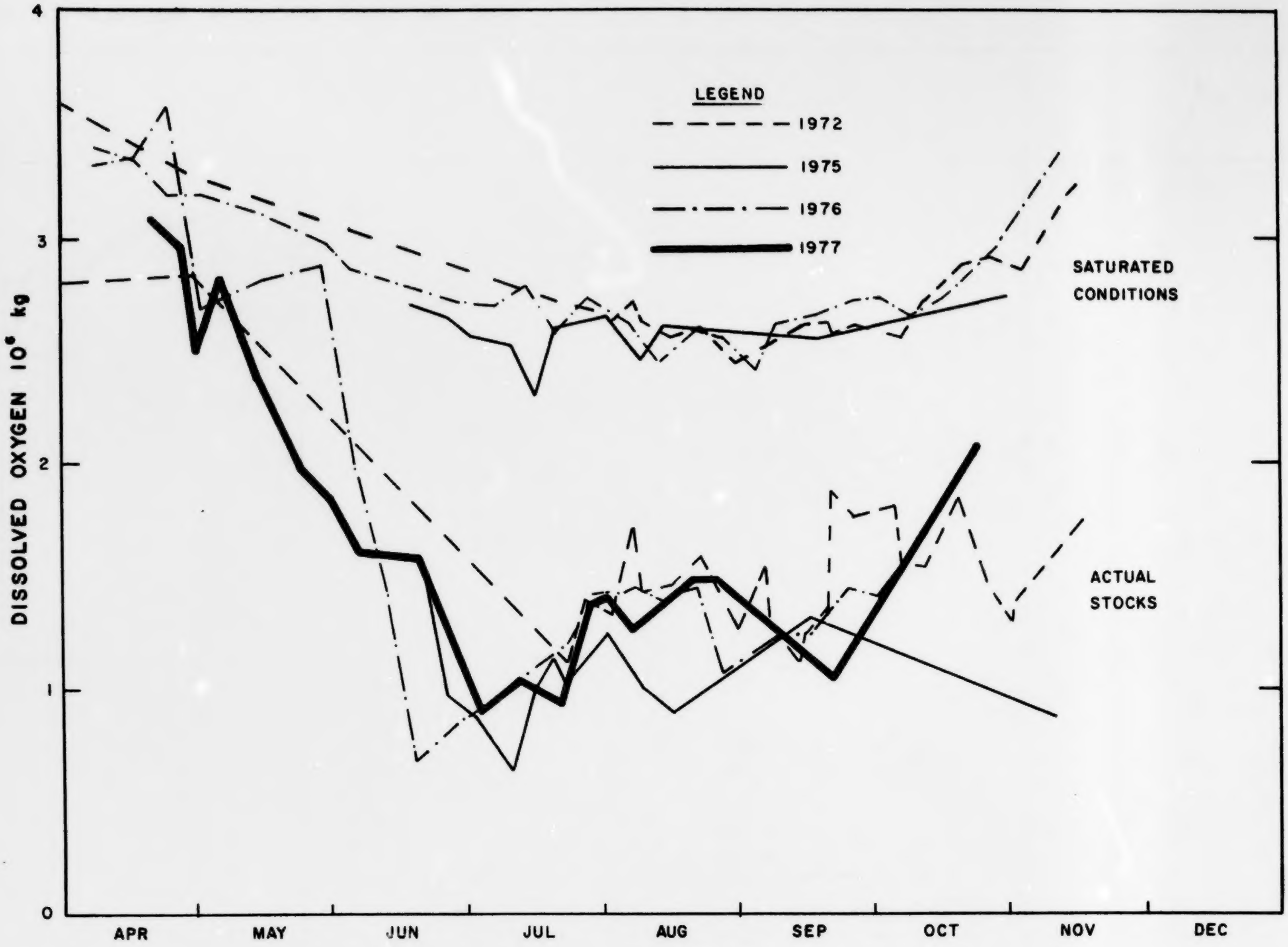

FIGURE 2 HAMILTON HARBOUR, DISSOLVED OXYGEN STOCKS.

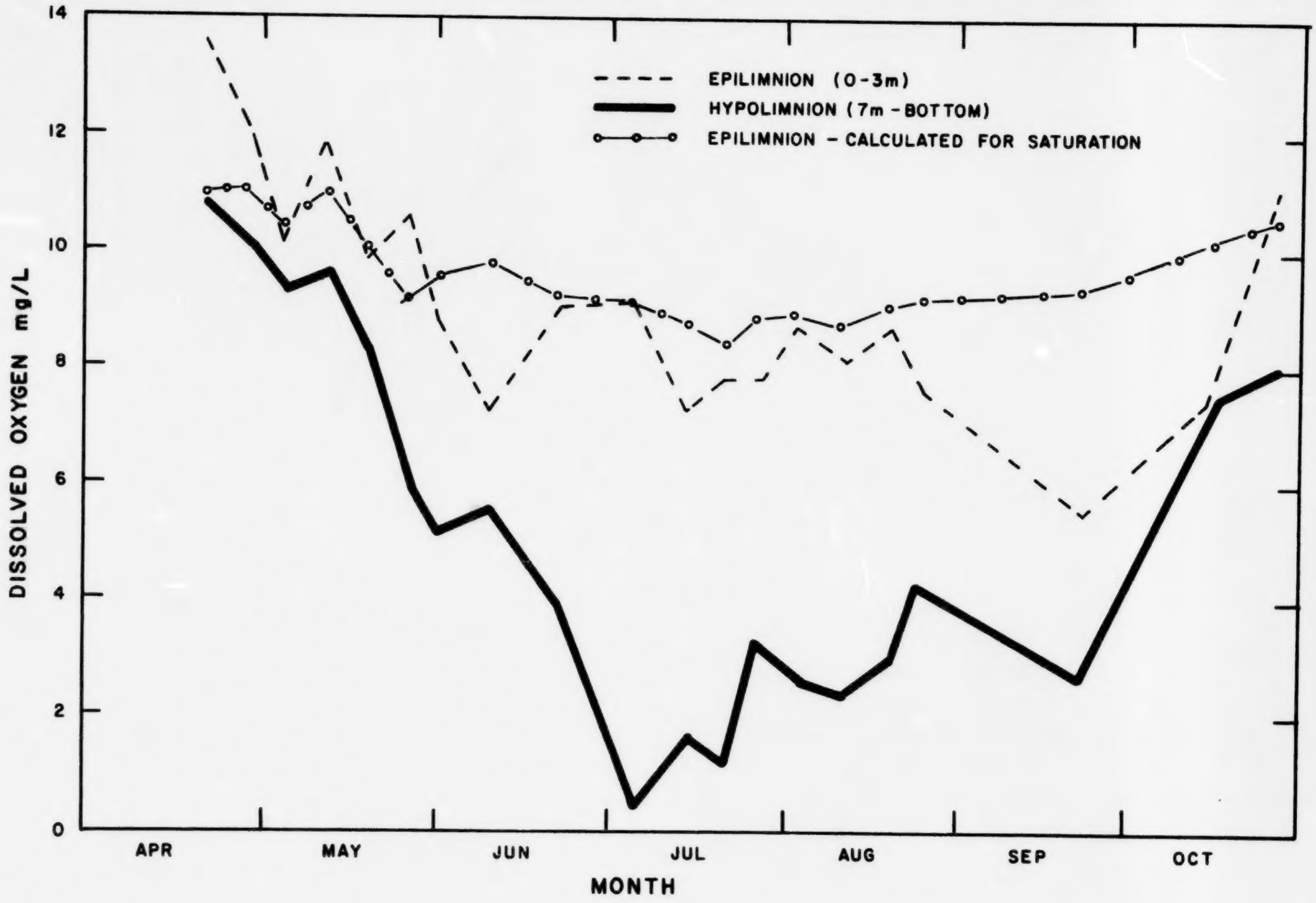

FIGURE 3 HAMILTON HARBOUR, 1977. AVERAGE DISSOLVED OXYGEN CONCENTRATIONS.

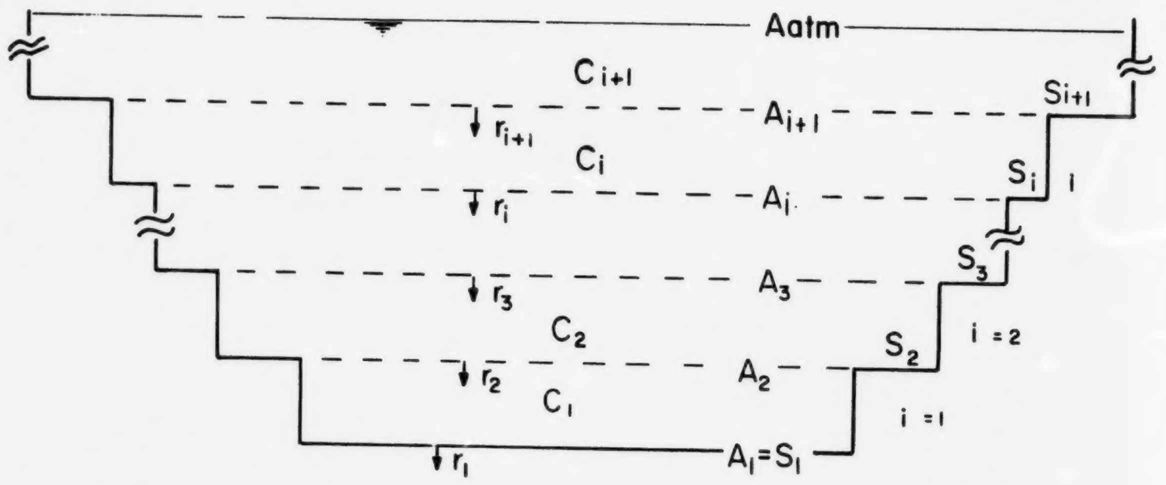
Aatm
C_{i+1}
S_{i+1}
r_{i+1}
A_{i+1}
C_i
S_i
i
r_i
A_i
S_3
r_3
A_3
C_2
i = 2
S_2
r_2
A_2
C_1
i = 1
r_1
$A_1=S_1$

FIGURE 4 VERTICAL EXCHANGE MODEL.

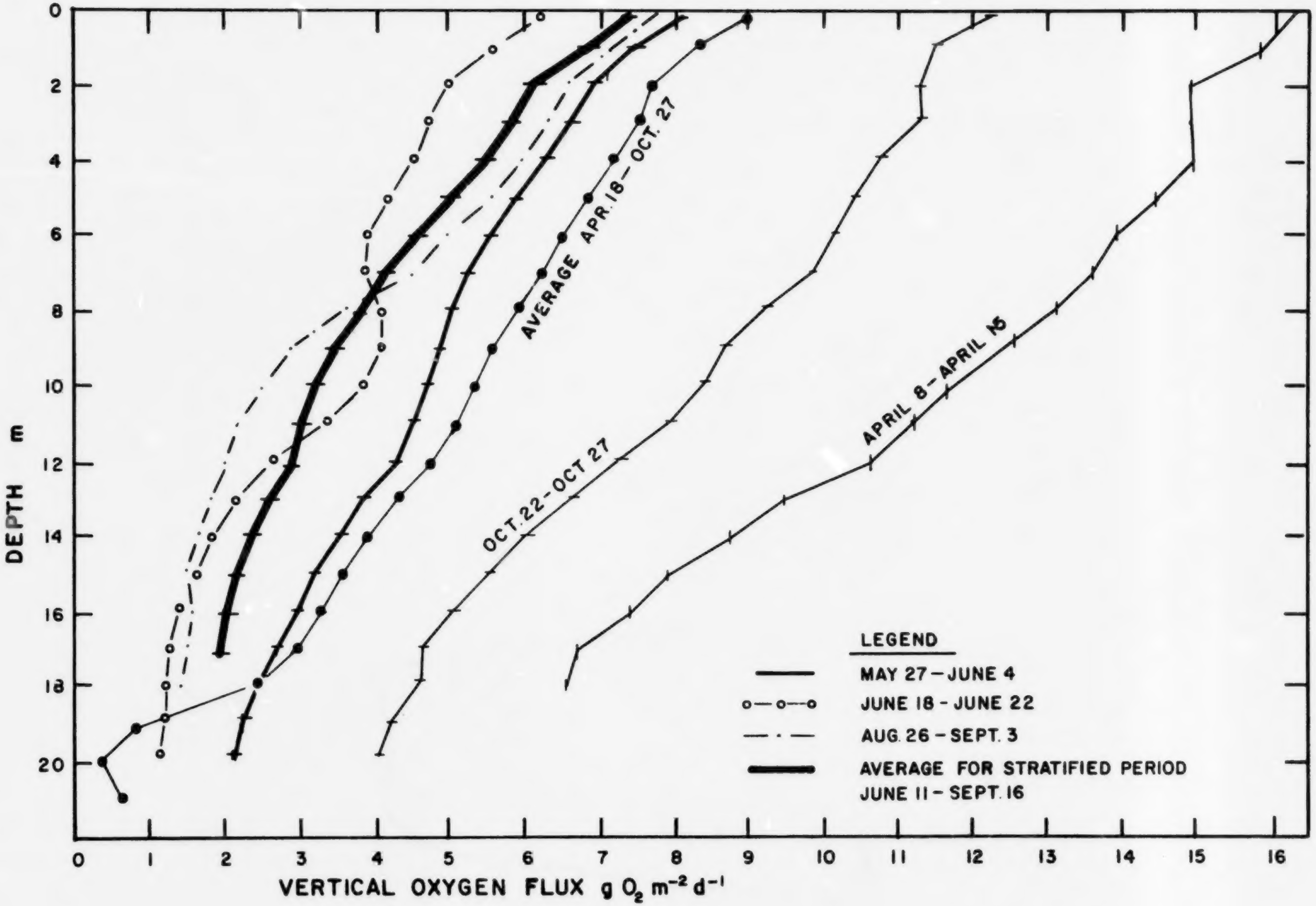

FIGURE 5 AVERAGE VERTICAL TRANSPORT OF OXYGEN IN HAMILTON HARBOUR, 1976.

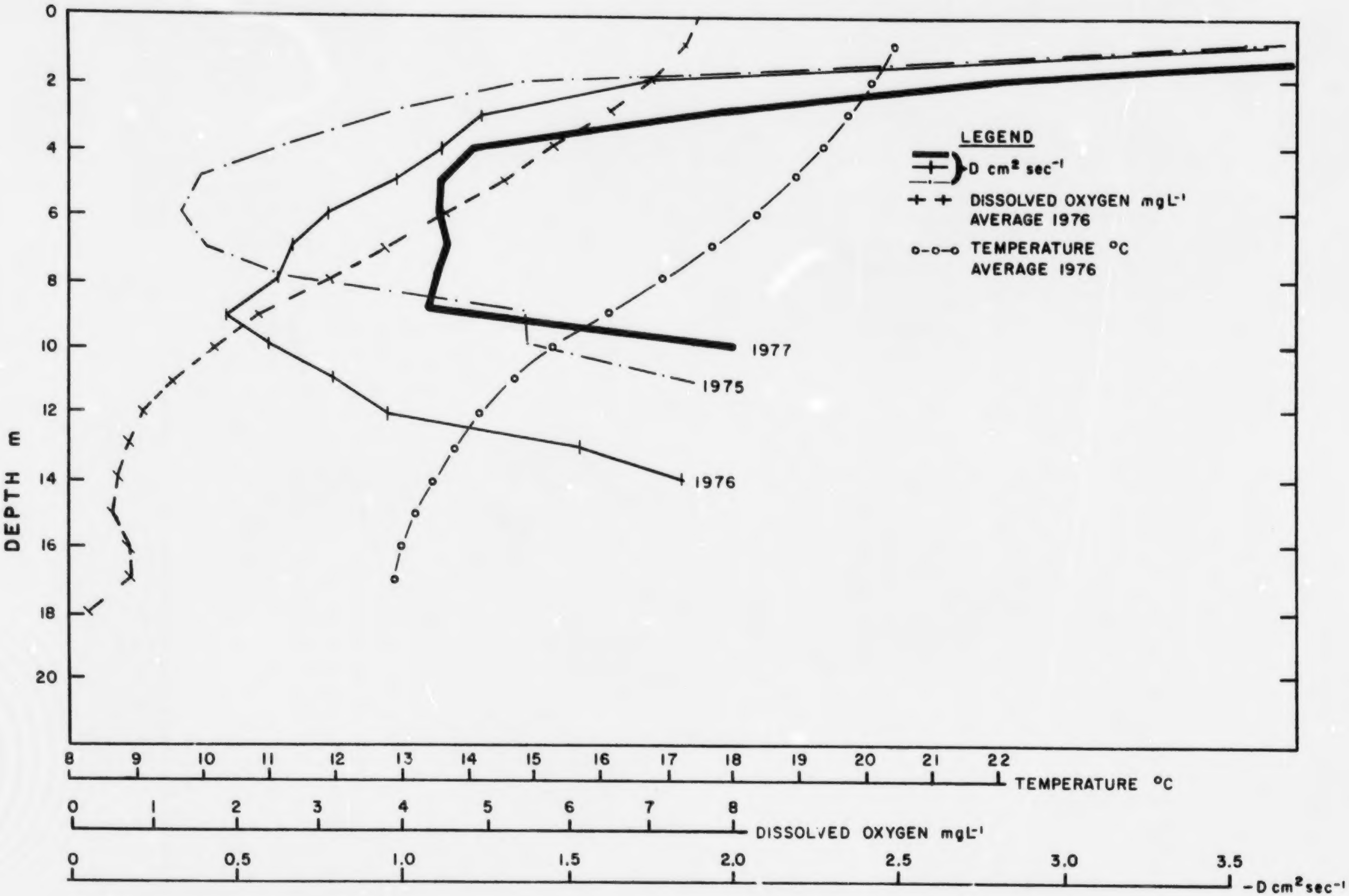

FIGURE 6 AVERAGE WATER COLUMN PARAMETERS OVER STRATIFIED PERIOD JUNE 11–SEPT 16, 1976.

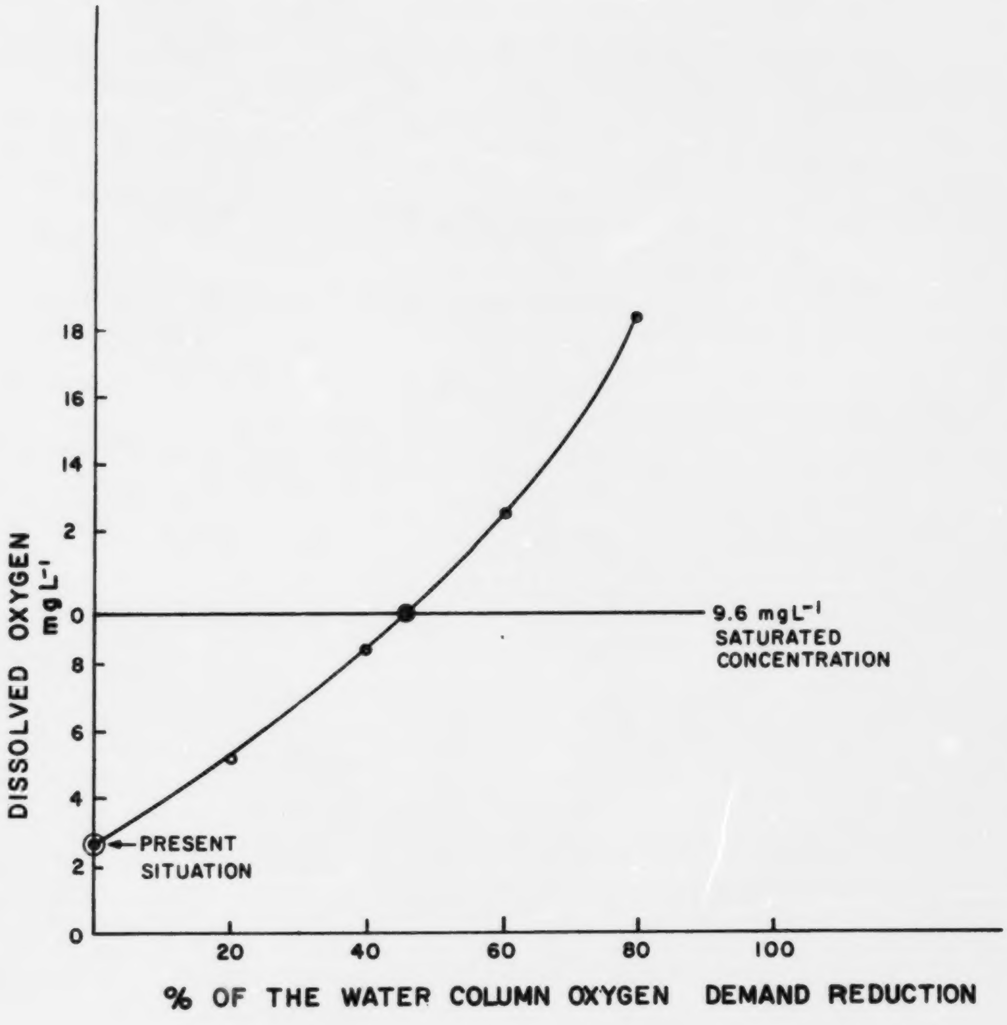

FIGURE 7 ESTIMATED FINAL CONCENTRATION ON JUNE 18, 1976 FOR DIFFERENT REDUCTION OF WATER COLUMN OXYGEN DEMANDS.

HAMILTON HARBOUR STUDY

1977

Volume I

SECTION C

WATER CHEMISTRY

SUMMARY

The water quality survey initiated in 1975 was continued during 1976 and 1977 to assess the effectiveness of the artificial mixing program and extend the knowledge of harbour water quality trends. In addition, a survey of nutrient and organic chemical pollution at storm water outfalls was conducted in 1977.

Dissolved oxygen results in both years showed the effect of water column instability, lake water intrusion and artificial mixing. Midsummer DO values next to the sediment were as high as 6 mg/L at station 4 and 3 mg/L at station 258.

Ammonia values in spring 1977 were considerably higher than those observed in recent years with the mean value being 5 mg/L. According to outfall survey samples, the source of the higher ammonia appeared to be the Hamilton WPCP. The seasonal nitrate pattern was dominated by a strong nitrification peak at the end of June which coincided with the time of maximum harbour BOD. Maximum nitrate values (in July) averaged 2.6 mg/L.

Total phosphorus values were slightly lower at 0.06 mg/L in 1976 than in 1975. In 1977, dissolved phosphorus results were slightly higher at the east end of the harbour. Otherwise, there were no significant changes in this parameter.

Silica concentrations were again higher in the hypolimnion than in the epilimnion in both years. In August 1976, however, an unusually high hypolimnetic silica concentration occurred throughout the harbour.

No significant seasonal or year-to-year trends in iron and zinc concentrations were found in the period 1975-77. Mean iron and zinc concentrations were 0.3 and 0.08 mg/L, respectively. This zinc concentration is high enough to cause a potential algal toxicity, but the extent of toxicity is dependent upon such factors as chemical speciation and interaction with other metals.

Determinations of organic matter in the harbour by chemical and biochemical oxygen demand and total organic carbon indicated that these parameters are not correlated with one another. This situation has been frequently observed in natural waters and occurs because the different tests measure significantly different substances. Each parameter varies significantly with sampling date; maximum BOD values were found in June at a time corresponding to the maximum nitrification rate. The observed correlation of dissolved organic carbon with BOD suggests that organic carbon plays an important role in the water column oxygen demand. Most of the industrial, municipal and storm water outfalls are sources of dissolved organic carbon.

INTRODUCTION

As part of the multi-year water quality study in Hamilton Harbour, an intensive survey program established in 1975 was continued in modified form during 1976 and 1977. The same four stations (4, 252, 258, and 270; Figure 1) were used and three to five depths per station were sampled according to the total water depth. In 1976, the harbour was surveyed once every two weeks from late April until the commencement of artificial mixing in June, and then approximately weekly until late August, and irregularly thereafter. In 1977, surveys were done every two weeks from late April to mid-October. Some monthly sampling runs for nutrients (8 stations in 1976 and 10 stations in 1977) were also done. In addition, detailed depth profiles of temperature, dissolved oxygen, redox potential, pH, and conductivity were obtained by NERA water quality monitoring, approximately weekly during both field seasons. During 1977, a survey of stormwater runoff flow and chemistry was also conducted. This consisted of continuous conductivity, half-hourly temperature and dissolved oxygen, and hourly biological oxygen demand (BOD), chemical oxygen demand (COD), total organic carbon (TOC), and filtered organic carbon (FOC) measurements for six hours at the locations shown in Figure 1a, approximately three times per location. One sample for nutrients (N and P) was also taken during each survey. The purposes of the chemical survey were to extend the knowledge of water quality trends in Hamilton Harbour, to assess the dissolved oxygen deficit and measure the effects of abatement procedures in operation. The purpose of the stormwater survey was to obtain accurate real-time histories of flows and water quality at the storm sewer outfalls, suitable for input to the numerical models, as well as improving our knowledge of the time variation of the harbour processes.

Details on the artificial mixing procedure and the results obtained are covered in Section A, Artificial Mixing. Measurements of sediment and water column oxygen demand and their contributions to harbour dissolved oxygen stock has been covered in detail in section B, Oxygen Budget. The dependence of water nutrient and heavy metal concentrations upon events at the sediment-water interface is discussed with respect to a series of proposed experiments on sediment extraction and sediment-water exchange in Section D, Sediment Chemistry.

This section consists mainly of a water quality update in which the trends in previously measured parameters are extended to 1977 and comparisons of water quality data for the interval 1972-77 are discussed with reference to the above-mentioned sections, where appropriate. As in the 1975 report, it has been broken down into several subsections to facilitate discussion of the harbour quality with respect to several chemical parameters. In this section the effect of the control procedures has been included where appropriate.

REDOX POTENTIAL AND DISSOLVED OXYGEN

In Figure 2, the depth-time distributions of redox potential are plotted for 1976. As in 1975, all results indicated potentials much lower than expected for oxygenated surface waters (Hutchinson, 1957) with average values being about 200 mv and considerable fluctuations occurring during the period of artificial mixing.

As discussed in the 1975 report (MOE, 1977), it is difficult to explain the redox potential results. Various explanations suggested include exposure of the redox probe to sulphide - containing sediments (which produces a platinum sulphide film resulting in low, drifting potentials), or various iron redox couples. Equipment malfunctions during 1977 resulted in no reliable redox data being obtained for that year.

Isopleths of dissolved oxygen results obtained at the four major sampling stations are given in Figure 3 for 1976 and Figure 4 for 1977. Periods of anoxic or near-anoxic conditions (DO < 1 mg/L) are indicated by shaded areas. The data for both years show the effect of harbour instability as a series of oscillations in the depth of constant DO values during the summer months at a depth of 6 to 10 m. These apparent oscillations are due to the internal wave structure within the harbour caused by the effect of Lake Ontario as well as wind-induced oscillations.

In 1976, the aerator supplied flows close to the critical value of 0.14 m^3s^{-1} (300 cfm) for most of the period from mid-July to the end of August (section A, artificial mixing). In 1977, the aerator produced flows above 0.14 m^3s^{-1} only for the last three weeks of July; average flows were 0.11 m^3s^{-1} in August and 0.09 m^3s^{-1} in the period June 13-July 10. By comparison of these dates with the DO-depth data given for stations 4 and 258 in both years, it is apparent that oxygenation of the near-bottom waters, which reached a peak in July of both years, and was stronger at Station 4 than 258, is a combined effect of the artificial mixing with the harbour-lake exchange. Colder lake water entering the harbour sinks to the appropriate density level and mixes with harbour water, but produces a stronger effect near the ship canal. However, this phenomenon should occur for a greater portion of the summer and not be concentrated within a period of a few weeks. In addition, the efficiency of the mixing in August 1976 was as good as that in the last half of July, but DO levels remained below 1 mg/L throughout August at both stations 4 and 258.

In 1977, hypolimnetic dissolved oxygen values were significantly higher than in 1976, except perhaps after mid-August, when near-anoxic results were observed at the two deep locations. The largest change was observed at station 4 during June (compare Figure 4a with Figure 3a). As aerator flow before mid-June was negligible, this is a strong indication of the effect of harbour-lake exchange. In addition, the highest dissolved oxygen recorded in the hypolimnion of station 258 occurred on July 5, just before optimum aeration was achieved. DO values at this location dropped below 1 mg/L late in July but increased slightly above 1 mg/L for part of August. It cannot be said how much of this effect was due to the aerator.

Figure 5 shows a series of dissolved oxygen-depth profiles taken July 13, 1977 on a roughly east-west line between the canal and station 258. This shows mixing of lake and harbour water due to lake water intrusion as far west as station 254, with apparently two lenses of higher DO water at station 254. Lower dissolved oxygen near the bottom at station 269 may have been due to short-term harbour instability; profiles taken at this location on other dates in 1975-77 have sometimes shown bottom DO values of greater than 8 mg/L. The effect of lake water on the vicinity of station 4 was also shown by the low pollutant concentrations in the sediments and similarity to stations 269 and 1030 observed in 1977, as well as the mixed conditions at station 255 seen in several sediment sampling surveys (see section D, Sediment Chemistry). The effect of lake water intrusion and mixing on the harbour DO is to be studied further in 1978 using the three-dimensional numerical model.

Experimental studies of sediment-oxygen demand and computation of the harbour DO stock has been discussed elsewhere (Section D, Oxygen Budget) and will not be repeated here.

NITROGEN

Data for 1976 and 1977 can be compared with results of previous years using techniques similar to those used in previous reports. Tables 1 and 2 show June-October surface averages for ammonia and nitrate at several stations as well as monthly surface means for the entire harbour. The June-October means were not computed in 1977 as a different set of sampling stations was used. Figures 6 to 16 show trends for ammonia, total Kjeldahl nitrogen, nitrite-N and nitrate-N displayed for: (a) seasonal trends of harbour-wide surface means for 1972-77; (b) 1976 isopleths; and (c) 1977 isopleths.

The most striking change in any nitrogen parameter is the dramatic increase in spring NH_3-N values in 1977, compared to 1975-76 (Figure 6). Peak average values approached 5 mg/L, with station 4 achieving a maximum of 6.3 mg/L on May 11. Observed results are comparable to 1972 figures, though the May 1972 peak was not sampled and may have been higher. A 10-station survey on June 9, 1977, yielded a result of 5.7 mg/L at station 20 in the southeast part of the harbour, 3.55 mg/L at station 4 and 3.55 mg/L at the other eight locations sampled. Two other surveys in 1977 also showed much higher concentrations at station 20. Although this was also true in 1976, the 1977 mean (3.65 mg/L) was far higher than the 1976 mean

(2.35 mg/L); it appears as though more NH_3 is being discharged from the Hamilton sewage treatment plant or other location in this area. Outfall surveys in 1977 (Table 3) indicated the worst NH_3 contamination to come from location 274 (Hamilton sewage treatment plant), with severe contamination originating also at other southeastern locations (220, Strathearne Street slip; 211, ditch carrying industrial effluent to Kenilworth Street slip; and 225, Parkdale Street). Values at all of these locations ranged upwards of 5 mg/L NH_3-N to a maximum of 18 mg/L NH_3-N (Table 3).

Following the spring peak, the surface and bottom NH_3 concentrations decreased rapidly, such that July concentrations were comparable in each of 1975-77. In August, surface NH_3 concentrations were slightly higher in 1976 and 1977 compared to 1975. During both years, epilimnetic ammonia concentrations were higher than hypolimnetic in the summer period (June-August), reflecting the surface nature of the discharges. Surface NH_3-N concentrations are still considerably higher than the public surface water supply criterion of 0.5 mg/L for most of the season.

The seasonal and depth variations of total Kjeldahl nitrogen (figures 9-11) parallel those of ammonia. This reflects the fact that the organic N content (TKN less NH_3-N) of the harbour is roughly constant with time, exhibiting only irregular seasonal fluctuations. Most, but not all samples obtained in July-August 1976 and June-early August 1977 exhibited organic N concentrations of around 1 mg/L while average concentrations before and after this period were 0.4 to 0.7 mg/L in 1976, and 0.6 to 0.8 mg/L in 1977. This tendency toward higher summer organic N values does not correlate with other parameters such as NO_2-N, chlorophyll a, or total organic carbon. Organic N concentrations in both years were somewhat smaller than 1975 averages of 1-1.5 mg/L.

The highest organic N concentration observed in 1977 at stormwater outfalls was about 10 mg/L. This value was obtained at locations 211 (drainage ditch to Kenilworth Street slip) and 225 (Parkdale Street outfall). Both of these sewers are contaminated with industrial wastes.

Nitrite concentrations did not exhibit the extreme values picked up in 1975 (harbour-wide mean 1.1 mg/L NO_2-N on June 4, 1975). On June 14, 1976 and July 13, 1977, epilimnetic average concentrations of 0.35 mg/L NO_2-N were recorded; concentrations of 0.25 to 0.3 mg/L NO_2-N were also observed in late August to early September of both years, while NO_2-N concentrations of most other samples were below 0.2 mg/L. Epilimnetic concentrations tended to be slightly higher than hypolimnetic concentrations during most of the summer period. The variability of this parameter was too irregular to allow correlation with the operation of the aerator or any other chemical parameters.

The general form of the seasonal surface nitrate curve (Figure 14) was similar in each of the years 1975-77, although the nitrification peak in 1976 occurred several weeks earlier than in 1975 or 1977, and the 1977 nitrification maximum was higher than any year since 1970 (see Table 2). The nitrification peak in both 1976 and 1977 coincided with the time of maximum BOD, on a harbour-wide average basis (Figure 24). In 1977, the nitrification peak is also related to the high spring ammonia values, although only a portion of the ammonia-N peak is nitrified. Total inorganic N, or $(NH_3 + NO_2 + NO_3)$ - N gradually decreased from a mid-May maximum indicating a net biological uptake of N or denitrification.

Combined seasonal-depth variations of NO_3-N in 1976 and 1977 (figures 15-16) are less clear than they were in 1975, when a period of nitrification or sediment release during June was followed by denitrification under late summer hypolimnetic anoxia. In early June of 1976, nitrification or N release at the sediment-water interface allowed a build-up of NO_3-N in the hypolimnion of the deep water stations. With the onset of anoxic conditions an irregular decrease in hypolimnetic NO_3-N occurred, with a minimum value being reached July 20. This was close to the time at which efficient (0.14 m^3s^{-1}) aerator operation was established. However, this decline was interrupted by a period of NO_3-N increase between July 6 and 13. This was during the period in which dissolved oxygen was being supplied to the lower hypolimnion by artificial mixing and lake-harbour exchange as discussed earlier. During early August, a gradual release or build-up of bottom NO_3-N occurred, apparently connected with aerator operation; however, epilimnetic nitrate concentrations remained higher than hypolimnetic concentrations for most of the summer. After late August, denitrification occurred at the sediment-water interface, under near-anoxic conditions. The trend of NO_3-N concentrations in the deepest waters, however, seemed to parallel the existence of oxidized conditions at the sediment-water interface.

In 1977, however, the seasonal-depth variations of NO_3-N are harder to explain. Throughout most of the summer, epilimnetic NO_3-N concentrations were higher than hypolimnetic concentrations. Nitrification at the bottom appeared to occur only around the end of June, when rapid nitrification of ammonia was occurring throughout the water column. This occurred before efficient operation of the artificial mixing device had been achieved, but while considerable DO was still present in the hypolimnion at the east end of the harbour (figure 4a). Before the end of June, despite the continued presence of DO next to the sediment at least at station 4, irregular behavior occurred; whereas one might have expected a heavy NO_3 build-up during this period leading to a condition of hypolimnetic NO_3-N > epilimnetic NO_3-N. The reason for the lack of the expected trend is unclear, unless it is related to bacterial or phytoplankton populations. After mid-July, a tendency to decreased NO_3-N concentrations at the bottom occurred, despite aerator operation and DO values between 1 and 2 mg/L. This is again in contrast to 1976 results. Such a decrease in NO_3-N concentration may be caused by nitrate assimilation by phytoplankton (Hutchinson, 1957). Alternately, denitrification within the sediments may be responsible (and thus indicative of anoxia within a few mm of the sediment-water interface). This is, however, at variance with 1976 observations; this difference cannot be explained at this time.

Nitrate values obtained at storm water outfalls (Table 3) were strongly affected by dissolved oxygen, owing to the high BOD and COD values generally exhibited. The highest NO_3 concentration was 8 mg/L in Red Hill Creek. Under DO values of less than 3 mg/L, nitrate concentrations were almost always below 1 mg/L.

PHOSPHORUS

Tables 4 and 5 give June to October surface means of total and soluble phosphorus for selected stations, and harbour-wide monthly surface means observed since 1967. Figures 17 and 18 present depth-time distributions of total phosphorus for 1976 and 1977, respectively, while Figures 19 and 20 present the same for filtered reactive phosphorus.

Year-to-year trends are difficult to discern from the means of total and soluble phosphorus as presented in Tables 4 and 5. Consequently, the annual surface means were compared from one year to the next for each station using the Student's t-test. The results are given in Table 5a. A significant decrease in total phosphorus occurred at three of the four locations from 1975 to 1976. Although the 1977 data suggested an increase from 1976, particularly in the 8- to 10- station survey data, the change was not statistically significant for total phosphorus. A significant increase in filtered reactive P did occur at stations 4 and 252 (east end of the harbour) from 1976 to 1977. It must be remembered that soluble phosphorus is affected by large analytical variability as well as possible changes between sampling and analysis. In addition, only three surveys were performed in 1977 on the 10-station grid, and one of these (August 10/77) coincided with a 4-station survey which produced the highest average soluble phosphorus value of the entire season. These factors prevent one from drawing any definite conclusion about changes in phosphorus content in Hamilton Harbour from the available data.

The worst areas of storm and sanitary sewer outfall contamination with regard to phosphorus are shown in Table 6. These areas are location 225 (Parkdale Street), 211 (sewer draining to Kenilworth Street slip carrying some industrial wastes), 273 (near Randle's Reef) and 274 (Red Hill Creek; Hamilton STP). Two of the five samples taken from location 274 exceeded the IJC guideline for maximum municipal sewage effluent total P of 1.0 mg/L.

No seasonal trend is exhibited in the 1976 or 1977 total and soluble P data. A tendency for epilimnetic total phosphorus values to be slightly higher than hypolimnetic values is observed at station 4 in both summers and stations 258 and 270 for parts of 1977. These changes are not noticeable in soluble reactive P.

Both parameters showed occasional pockets of high results, which sometimes occurred on the same date (e.g. August 10/77) at several locations. This phenomenon has been observed previously (MOE, 1974, 1977) but has not been explained adequately.

Little, if any evidence is available for release of total or soluble phosphorus from the sediments in either year. Any slightly higher soluble P values that do occur are not correlated to either decreased DO or increased dissolved iron levels. Piccinin (1977) found a very high (but unstated) level of soluble reactive phosphorus at station 4 near the end of August 1976. Such a peak may easily have occurred between successive MOE sampling dates and have been missed; certainly there is no evidence here to confirm or deny this peak. Piccinin (1977) indicated the hypolimnion to be anoxic at the end of August; MOE data indicated about 3 mg/L DO at the bottom on August 23, but the DO monitor failed to function properly on August 30 or September 7; consequently, no proof of hypolimnetic anoxia at the end of August is available.

Control of phosphorus concentration at the sediment-water interface, and proposed experiments to study this factor in more depth, are discussed in Section D, Sediment Chemistry.

SILICA

The seasonal variation of dissolved reactive silica (as Si) is shown as surface and bottom means in Figures 21 and 22 for 1976 and 1977, respectively, and in isopleth form for 1977 in Figure 23. Although a general similarity is apparent from 1975 (MOE, 1977) to 1977, differences are evident in each annual curve.

In spring 1976, Si concentration was 0.6-0.8 mg/L, far lower than the 1.0-1.5 mg/L observed in 1975; consequently, the early summer minimum was reached earlier (mid-June) and with lower concentrations. With development of thermal stratification, epilimnetic Si concentrations become lower than hypolimnetic, as in 1975; in July the concentrations again become homogeneous, presumably in response to artificial mixing, again as in 1975. However, the most homogeneous results occurred before optimum air flow was achieved, but at a time when hypolimnetic DO values were highest (see discussion on DO). In August 1976, irregular changes in Si concentration developed, along with a considerable increase in bottom Si. On August 17, large variations in Si content occurred across the harbour; the bottom Si concentration reached 1.1 mg/L at station 258 while surface Si concentration was 1.15 mg/L at station 4 and 0.10-0.15 mg/L at other points. By contrast, the Si concentration at 3 m depth at station 4 was 0.25 mg/L; below this depth, the typical stratification (hypolimnetic Si   epilimnetic Si) had reappeared. This stratification persisted, with declining average values, until fall turnover. Although the bottom water at station 258 was near-anoxic at the appearance of high Si, the Fe concentration was negligible, suggesting that the high Si is not due to reduction of silicates at the sediment-water interface. Perhaps another metal is involved; or massive decomposition of diatoms could have released dissolved Si to the water column at this time. Hutchinson (1957, p. 794-5) suggests that silica can enter water from the sediments without complete anoxia. He suggests that diffusion of silica may be under control of temperature, but does not state why this should be so.

The 1977 Si curves resemble the 1975 data more closely than the 1976 period; however, the stratification did not develop until late June, suggesting a delay in maximum diatom growth. In addition, the apparent homogeneous Si concentration at the end of July was not due to artificial mixing but was caused by a relatively high (0.45 mg/L) value at station 4. (See also Figure 23.) Although Si concentrations were somewhat lower in July-August 1977 then in the same part of 1975 and 1976, weak depth stratification did persist throughout the harbour in this period as Figure 23 indicates. Possibly a larger crop of diatoms may be responsible. These may have decomposed during autumn cooling and turnover, producing the relatively larger increase in dissolved Si concentration seen in the September-October 1977 period.

HEAVY METALS

In 1976 and 1977, iron and zinc were determined from all sampling points at every survey. The purpose of determining zinc was to assess the extent of toxicity to the harbour algae. Piccinin (1977) determined that zinc has a toxic effect on the alga Scenedesmus quadricauda at concentrations above 0.01 mg/L, although she states that algae cultured from Hamilton Harbour show an increased tolerance to zinc toxicity and that response of various species to zinc concentrations below 1 mg/L is inconsistent.

As the zinc and iron concentrations showed no consistent spatial and depth variations and only irregular seasonal variations, harbour-wide monthly means were calculated. These data are given in Table 7. Mean zinc values range from 0.02 to 0.14 mg/L, with maximum individual results being 0.45 mg/L in 1976 (station 258, July 6) and 0.46 mg/L in 1977 (station 270, June 29). Mean iron values are about 0.3 mg/L, with occasional high values above 1.0 mg/L observed in the epilimnion at station 4. No significant year-to-year trends are evident in either metal. No evidence of release of iron from the sediment-water interface was noted; the highest bottom Fe values observed in 1977 occurred at station 4 on June 15 and July 27 (0.7 mg/L) while the bottom dissolved oxygen was around 4-5 mg/L. By contrast, in August 1977 when the bottom DO was 1 mg/L or less at station 4, the iron concentration was 0.3 to 0.5 mg/L.

A few samples were analyzed for manganese. Most results were below 0.1 mg/L in the spring and fall; in September 1976 a hypolimnetic increase was observed at stations 4 and 258, where values of 0.2 to 0.5 mg/L were found. This result is reasonable because manganese is released under less severe reducing conditions than iron. The redox potential to obtain 10^{-5} M (about 0.6 mg/L) concentrations of Mn and Fe corresponds to a pE of about 8 for Mn and 2 for Fe at a pH of near 7 (Stumm and Morgan, 1970, p. 533).

The iron and zinc values may be compared to the Great Lakes water quality objectives (IJC, 1977), which state that iron should be below 0.3 mg/L and zinc below 0.03 mg/L. It is seen that zinc concentrations are greater than objective values most of the time, and that average iron concentrations just barely meet the IJC objective. That this is true is not surprising since the harbour sediments are known to be highly polluted with respect to these metals (Section D, sediment chemistry; MOE, 1977, Section C).

Water samples were analyzed on one occasion only (May 11, 1977) for mercury. All samples were below 0.03 ug/L, indicating no problem in the water column for this metal. On the same date, aqueous copper was below 0.01 mg/L.

Environmental aqueous heavy metal concentrations are strongly regulated by events occurring at the sediment-water interface (for example, see Hutchinson, 1957; Stumm and Morgan, 1970, and references therein). Relationships between iron and phosphorus within the water column and at the interface in Hamilton Harbour have already been explored (MOE, 1974, Section D). Studies of sediment samples obtained in Hamilton Harbour in the period 1975-77 have suggested that control of heavy metal and phosphorus release from the sediment may be more complicated than the simple iron-phosphorus-dissolved oxygen system (see Section D, Sediment Chemistry, and MOE, 1978).

Although most heavy metals become less soluble under oxidized conditions (Stumm and Morgan, 1970), zinc may become more soluble at higher redox potentials (Hem, 1972). Equilibria involving zinc carbonate or hydroxide in water of composition similar to Hamilton Harbour predict a zinc concentration of about 10^{-6} M (0.65 mg/L) at a pH of between 8 and 8.5. Silicate equilibria predict a concentration of 10^{-7} M (0.06 mg/L) at a pH of 8 and a silica concentration of 10^{-4} M (2.8 mg/L as Si). This zinc concentration is approximately that observed in the harbour water. Equilibrium concentrations decrease at higher pH. Under reducing conditions, ZnS precipitates over a very wide pH range. Examples given by Hem (1972) tend to support silicate control of zinc solubility in many fresh waters, and it is possible that observed zinc concentrations in Hamilton Harbour are controlled by this equilibrium. If humic substances are present at a concentration of 5 mg/L or more, increased zinc solubility as humic complexes will occur (Wilson, 1978). This may occur at the dissolved organic C concentrations present in Hamilton Harbour, but these interactions are highly dependent on the nature of the organic material present.

Chemical speciation of toxic heavy metals in the water column is important in controlling their solubility and toxicity to biota. An initial study of heavy metal speciation in Hamilton Harbour was performed by Chau and Lum-Shue-Chen (1974), who analyzed "labile" (ionic and rapidly exchangeable complexed) and strongly bound concentrations of Zn, Cd, Pb and Cu in a Hamilton Harbour sample. They obtained concentrations in ug/L for strongly bound metals as follows: Zn, 27; Cd, 2.4; Pb, 1.3; and Cu, 49. The only detectable labile metal was Zn, at a concentration of 7 ug/L. Mancy and Allen (1977) reviewed the effect of organic complexing agents on heavy metal toxicity in detail, with particular reference to copper. Although some disagreement exists in the literature, they observed that in general organic chelating agents such as polypeptides or humic acids considerably reduce the toxic effect of heavy metals.

An additional factor of importance in toxicity studies is the interaction between different heavy metals. At times, the full toxic effect of one metal may not be observed in the presence of a second metal (United Nations, 1976). This was indicated for the pairs cadmium-zinc, lead-calcium, and mercury-selenium. The effect of cadmium may thus be responsible for the increased tolerance of S. quadricauda to zinc toxicity and inconsistent responses mentioned above. On the other hand, increased toxic effects have been observed in the combination mercury-lead-zinc (United Nations, 1976). A recent study of heavy metal toxicity to S. quadricauda (Wong, Chau and Luxon, 1978) revealed a synergistic toxic effect of a mixture of ten metals each present at the IJC (1977) recommended maximum concentration. The same study showed an additional toxic effect of Hamilton Harbour water on S. quadricauda compared to a test growth medium. Certainly the mechanisms involved in heavy metal algal toxicity are complex.

Further studies on aqueous heavy metal concentrations in Hamilton Harbour would have to include determining metal speciation. This involves complicated electrochemical techniques such as anodic stripping voltammetry (Chau and Lum-Shue-Chen, 1974; Mancy and Allen, 1977) which are at present beyond Ministry laboratory capabilities. However, studies in this field would correlate well with proposed and existing studies on sediments and heavy metal toxicity.

ORGANIC POLLUTION AND OXYGEN DEMAND INDICATORS

In 1976, surface and bottom water samples from each location were analyzed for biochemical and chemical oxygen demand (BOD and COD), and total and filtered organic carbon (TOC and FOC). In 1977, samples from all depths and locations regularly used were analyzed for these parameters. In addition, samples from the stormwater outfall locations (Figure 1A) were collected hourly for 6-hour periods on each of two to four days during 1977, in an effort to measure the magnitude and time variation of oxygen demanding loadings to the harbour.

To assess the extent of variability of these parameters and their relationships with one another, statistical methods of correlation analysis and analysis of variance were used, with emphasis on the 1977 data due to the larger amount of information available. Three-way analysis of variance (depth-station-date) indicated that BOD, COD, and TOC all varied significantly at the 0.1% level with respect to sampling date. TOC exhibited a significant variation at the 1.0% level with respect to depth. Variation of other parameters with respect to depth, and of all parameters with respect to sampling station, was not significant.

These parameters were next correlated with one another on the basis of harbour-wide means for each sampling date. As the results were highly variable and frequently indicated negative correlations, it was decided to correlate all 1977 data together. Turbidity and suspended solids were included in order to ascertain any relationships with particulate matter. FOC was not included at this stage as analyses for it were not done on all 1977 sampling dates. The results, given in Table 8, indicate no significant correlations between any of these parameters, except for the expected turbidity-suspended solids relationship. The lack of relationships between TOC and turbidity or suspended solids is not surprising in view of the fact that FOC made up over 90% of TOC in most samples tested.

To further explore the significant variations with sampling date and the lack of observed inter-correlations, and facilitate inter-year comparisons, harbour-wide means of each parameter were plotted against sampling dates for 1976 and 1977. These data are given in Figures 24 (BOD), 25 (COD), and 26 (TOC). Error bars are ±1 standard deviation. TOC data were plotted in 1977 as surface and bottom means due to the observed significant variation with depth; bottom samples were displaced slightly on the time axis for clarity.

Figure 24 shows that in both years BOD exhibits a similar seasonal dependence, increasing to a June maximum followed by a decrease to a relatively constant value of 2-3 mg/L by the end of July. The 1977 peak mean (6 mg/L) was slightly less than the 1976 peak mean (8 mg/L). No significant changes occur for the rest of the season. It is interesting that the maximum BOD occurs at a time of the most rapid nitrification in the harbour, as well as when the harbour dissolved oxygen stock is decreasing rapidly. Normally, the 5-day BOD test measures largely carbonaceous biochemical oxygen demand; nitrogenous BOD is generally exerted at longer time intervals. In addition, nitrogenous BOD is not often well measured during the common BOD test as the nitrifying bacteria may not be well acclimatized to the conditions of the test (D. Weatherbe, personal comm.). Studies in the Grand River basin (MOE, 1976) showed that nitrogenous BOD made up a significant portion of the total BOD of sewage effluents. Additionally, an effect of nitrification on the measured BOD_5 values was observed by Chandler et al (1976) in a Massachusetts River. On the other hand, Hamilton Harbour Nitrosomonas populations in 1976 showed only an erratic seasonal dependence with no relationship to the observed BOD peak. The reason for this lack of correlation is unknown.

Unlike BOD, the seasonal dependence and year-to-year consistency of COD and TOC is less evident. COD shows very little seasonal changes in either year, with the significant variation in the 1977 analysis of variance likely related to the high values observed on June 29 and August 24. The former coincides with the BOD peak, while BOD was not measured on the latter date. The 1977 annual mean COD value (27 mg/L) was slightly higher than the 1976 mean (21 mg/L); unlike the BOD situation. TOC shows strange seasonal variations in both years, which do not relate to one another or to the other parameters. Surface TOC values in 1977 are slightly higher than bottom water values, as expected, considering the epilimnetic nature of the discharges to the harbour. No apparent relationship to the artificial mixing program is evident.

The lack of correlation between BOD, COD and TOC in natural water samples (as opposed to effluents) has been generally noted in the literature (for example, Chandler et al, 1976; Jones, 1972). This is not surprising as some organic chemicals resist biochemical oxidation and others resist chemical oxidation, but none resist the catalytic oxidation procedure of the TOC analysis. In addition, some inorganic materials such as ferrous iron and sulphide are oxidized during the COD test. The BOD test is also highly dependent upon the nature of the seed organisms used in the test; if these are unlike the bacteria naturally found in the water, the result cannot meaningfully relate to oxygen uptake data.

A weak but significant relationship (r=0.215) was obtained upon correlating BOD with FOC for all samples on the eight dates in 1977 in which these parameters were both measured. This supports the suggestion (G. Harris, personal communication) that dissolved organic carbon plays an important role in the water column oxygen demand. However, 5-day BOD undoubtedly represents only a small portion of available oxygen demand within the harbour, especially considering that the average water retention time (including lake-harbour exchange, industrial intakes and discharges) is about 100 days. Nevertheless, the dissolved organic carbon content does present a problem, as it represents the ideal substrate for heterotrophic bacteria which are probably controlling much of the water column oxygen demand (G. Harris, personal communication). Some possible sources of this FOC are the Ottawa and Kenilworth Street slips, the Hamilton WPCP, and outfall locations 273, 211, 220, and 225. More study is desirable in locating the sources of this FOC.

In Table 9, the 1976 and 1977 means of all BOD, COD, TOC and FOC data obtained within the harbour are compared to mean values of the same parameters obtained at the various storm and sanitary sewage outfall locations. Additional details on the outfall results will be presented in a separate report under preparation; in this context, it should be mentioned that concentrations observed at the various outfalls varied widely from day to day and even within a given day. Standard deviations of most outfall data in Table 9 are close to or greater than the means. Table 9 indicates that the most concentrated effluents entered the harbour at locations 273, 211, 225 and 274. Location 274 is Red Hill Creek, which contains the Hamilton WPCP effluent, while the other three locations all contain industrial wastes. Due to the large variability observed in the remainder of the data, none of the other means presented in Table 9 are significantly greater than the 1977 mean values obtained within the harbour as indicated on the second line of Table 9. Except for locations 250 and 212 (Ottawa and Kenilworth Street slips), which have high industrial effluent flow rates and perhaps 220 (also contaminated with industrial effluent), these locations do not present a problem under dry conditions. Although very few results were obtained under conditions of stormwater runoff, results that did occur under these conditions indicated possible problems. For example, at location 108, maximum BOD, COD, and TOC concentrations observed shortly after commencement of rainfall were 32, 207 and 56 mg/L; similar concentrations persisted one hour later, but concentrations had dropped considerably after two hours.

MINERAL CHEMISTRY AND CONDUCTIVITY

In the report on 1975 results (MOE, 1977), a model was described in which the conductivity of a water sample is calculated from the equivalent conductances of the component ions and ionic interaction effects (Rossum, 1975). This model was verified for single salt solutions and applied to Hamilton Harbour water samples. It showed that non-conservative (biodegradable) materials contributed 2-3% to the observed conductivity and that chloride and sulphate contribute an average of 36% to the conductivity, as compared to 29% for Lake Ontario and 22% for world mean river water.

Surface and bottom water samples at the four major locations were analyzed once in 1976 and twice in 1977 for chloride, sulphate, sodium, potassium, calcium and magnesium. In addition, nitrate, ammonia, pH and alkalinity were measured during each survey; carbonate and bicarbonate concentrations were calculated from pH and alkalinity using the second ionization constant of carbonic acid (MOE, 1977).

Observed concentrations and computed contributions to the conductivity of each sample are given in Table 10. Unlike the 1975 situation, where the calculated conductivity values were higher than the observed values by 6 to 12%, the calculated conductivities were within 5% of the observed values for all but one sample. These variations are better than the coefficients of variation (6-9%) observed in an interlaboratory comparison of Lake Ontario and Grindstone Creek conductivity samples (McGirr, 1974). It did not appear necessary to consider ion-pair formation as affecting conductivity, as was done in 1975 (MOE, 1977). Although this appears to indicate reasonable analytical precision, a deviation of the ionic balance is observed in the autumn samples of both years. Equivalent anionic concentrations were generally 5 to 8% higher than cationic concentrations. This indicates a systematic deviation in the analysis of one or more chemical parameters. That errors of this magnitude are not unusual was noted in an interlaboratory comparison study by Ekedahl and Rondell (1973), who noted that systematic errors are more important than random errors. Deviations of the ionic balance in May 1977 were in random direction, and less than 6%.

A larger deviation was indicated for the surface sample at station 270 on October 13, 1977, where the ionic balance deviation was 13% and the conductivity deviation was 7%. Examination of the data indicates that the sulphate result is probably too high; a value of about 50 mg/L, similar to that observed with other samples taken on the same date, would produce better agreement. This shows the usefulness of these calculations in checking analytical data and suggesting a parameter which may need re-analysis.

Ranges and seasonal variations of major ion concentrations are similar in 1976-77 to those observed in 1975, except for the increased ammonia concentrations in spring 1977 (discussed under Nitrogen) which appear to be balanced by slightly increased bicarbonate. Calcium and bicarbonate were also very slightly higher in fall 1977 compared to fall 1976. The contributions of chloride and sulphate to the conductivity of Hamilton Harbour water averaged 36% in November 1976 and May 1977, and 34% in October 1977. These figures are similar to 1975 results and are as expected, considering the major use of Hamilton Harbour as a receiving water for industrial and municipal wastes. If the non-conservatives are represented by the N parameters (ammonia and nitrate), the results in Table 10 indicate that non-conservative materials contributed 2 to 5% of the total conductivity in 1977, the increased range being due to high spring ammonia N levels.

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TABLE 1

Ammonia Surface Data, 1966-1977

(a) June-October averages for each station

				Station			
	20	256	257	258	262	265(270)	269
1966	7.3	5.5	3.5	3.4	3.7	3.3	4.2
1967	3.1	3.9	2.4	2.4	3.3	2.8	2.2
1968	5.3	5.3	3.7	3.0	4.6	4.1	3.8
1969	4.7	5.1	3.5	3.4	4.7	3.5	3.1
1970	7.8	7.7	7.0	6.3	8.3	5.9	6.9
1971	7.4	5.8	4.9	5.3	8.5	4.8	5.0
1972	2.6	2.0	1.3	1.6	2.8	1.2	1.7
1974	0.50	0.10	0.17	0.21	0.24	0.19	-
1975	3.5	1.4	1.1	1.1	1.1	0.9	1.3
1976	2.5	1.3	1.3	1.2	1.2	1.1	1.6

(b) Monthly and annual averages for entire bay

	Jun	Jul	Aug	Sep	Oct	Period
1966	6.0	4.2	3.6	3.1	4.7	4.4
1967	3.8	2.3	2.6	2.2	2.4	2.8
1968	6.8	4.7	3.4	3.0	3.1	4.3
1969	4.9	4.0	1.9	3.3	5.5	4.0
1970	8.9	6.8	7.3	6.4	3.5	6.9
1971	9.3	6.1	4.7	3.7	-	5.9
1972	-	2.4	1.9	1.6	1.5	1.9
1974	-	0.016	0.30	-	0.42	0.26
1975*	1.9	1.2	0.33	0.47	0.36	0.85
#	2.7	1.5	0.91	0.94	0.66	1.4
1976*	2.2	1.4	1.1	0.59	0.44	1.5
#	2.1	1.0	-	-	0.57	1.5
1977*	3.2	0.89	0.67	0.31	0.36	1.4
#	3.6	0.98	0.84	-	-	1.8

Note:
All figures are in mg/L as N
Analytical precision ± about 10%
Standard deviations of above figures (including station and time variations) are generally 30--50% of the means.
*4-station weekly surveys (biweekly in 1977)
#8-station monthly surveys

TABLE 2

Nitrate Surface Data, 1966-1977

(a) June-October averages for each station

				Station			
	20	256	257	258	262	265(270)	269
1966	0.93	1.25	1.27	1.03	1.01	1.20	1.11
1967	2.48	2.62	2.79	2.89	2.59	2.74	2.78
1968	0.95	1.13	1.38	1.27	1.31	1.30	1.19
1969	1.11	1.28	1.47	1.43	1.45	1.36	1.38
1970	1.36	1.45	1.99	1.85	1.84	1.81	1.73
1971	1.52	1.92	2.15	2.10	2.07	2.08	2.00
1972	1.27	1.64	1.70	1.78	1.71	1.73	1.61
1974	3.7	2.9	2.3	1.9	3.0	2.3	-
1975	1.87	1.88	1.81	1.86	1.89	1.91	1.88
1976	2.35	1.86	1.87	1.69	1.65	1.70	1.62

(b) Monthly and mean average for entire bay

	Jun	Jul	Aug	Sep	Oct	Period
1966	-	-	1.10	1.41	0.56	1.11
1967	1.30	3.84	3.95	1.85	1.16	2.7
1968	0.62	1.85	1.61	1.06	0.85	1.22
1969	0.84	1.82	1.69	1.34	0.94	1.35
1970	0.87	2.40	1.90	1.64	1.99	1.75
1971	1.42	2.22	2.18	1.50	-	1.97
1972	-	1.89	1.77	1.42	1.58	1.65
1974	-	2.6	3.5	-	2.5	2.9
1975*	1.81	2.04	2.05	1.90	1.82	1.92
#	1.30	2.55	2.03	1.74	1.67	1.86
1976*	1.64	2.05	1.54	2.28	1.68	1.81
#	1.56	2.07	-	-	2.01	1.80
1977*	1.30	2.61	1.92	1.79	2.27	1.88
#	1.14	2.78	2.08	-	-	2.00

Note: All figures are in mg/L as N
Analytical Precision + about 10%
Standard deviations of above figures (including station and date variations) are generally 30-50% of station means and 10-50% of monthly means.
* 4-station weekly surveys (biweekly in 1977)
# 8-station monthly surveys

TABLE 3

Outfall Areas with Highest Nitrogen Concentration, Hamilton Harbour, 1977

(a) NH_3 and TKN

Location	Typical Values, mg/l as N	
	NH_3	TKN
274	11-18	14-38
211	4.7-12	12-32
225	7.7-11.2	16-24
220	2.1-15	6.3-19
273	3.6-6.4	6.6-9.6

(b) NO_3

Location	Typical Values, mg/l as N
274	up to 8
220	up to 3.4
212 (surface and bottom)	up to 3.4

TABLE 4

Total Phosphorus Surface Data, 1967-1977

(a) June-October averages for each station

	Station 20	256	257	258	262	265 (270)	269
1967	.112	.091	.087	.067	.077	.103	.126
1968	.099	.060	.034	.035	.050	.092	.048
1969	.093	.084	.044	.043	.049	.061	.067
1970	.275**	.074	.036	.044	.054	.046	.065
1971	.279	.055	.033	.031	.037	.037	.040
1972	.172	.086	.072	.068	.065	.068	.078
1974	.088	.077	.052	.057	.065	.066	-
1975	.122	.072	.082	.054	.066	.058	.059
1976	.073	.077	.061	.046	.048	.069	.062

(b) Monthly and annual averages for entire bay

	Jun	Jul	Aug	Sep	Oct	Period
1967	.075	.081	.107	.120	.102	.095
1968	.048	.060	.058	.075	.068	.060
1969	.058	.048	.037	.087	.094	.063
1970	.099**	.091	.065	.078	.059	.078
1971	.091	.055	.072	.098	-	.073
1972	-	.087	.082	.088	.093	.088
1974	-	.067	.102	-	.057	.084
1975*	.082	.086	.069	.077	.063	.075
#	.084	.074	.082	.050	.069	.072
1976*	.064	.061	.053	.060	.044	.059
#	.077	.054	-	-	.075	.071
1977*	.073	.068	.063	.053	.060	.065
#	.098	.071	.087	-	-	.085

Note: All Figures are in mg/L as P
**One questionably high value was omitted
Analytical Precision ± 0.003 mg/L or 10%, whichever is greater.
Standard deviations of above figures (including station and date variations) are generally 50-100% of the means.
* 4-station weekly surveys
# 8-station monthly surveys (10 stations for 1977)

TABLE 5

Soluble Phosphorus Surface Data, 1967-1977

(a) June-October averages for each station

	Station 20	256	257	258	262	265 (270)	269
1967	.060	.060	.058	.056	.114	.100	.098
1968	.067	.023	.025	.022	.028	.047	.035
1969	.045	.041	.021	.027	.029	.031	.032
1970	.150**	.007	.016	.020	.013	.013	.013
1971	.101	.009	.004	.007	.004	.007	.012
1972	.057	.020	.017	.015	.016	.015	.020
1974	.016	.005	.002	.004	.010	.003	-
1975	.063	.016	.018	.016	.017	.014	.019
1976	.013	.009	.012	.011	.012	.014	.015

(b) Monthly and annual averages for entire bay

	Jun	Jul	Aug	Sep	Oct	Period
1967	.054	.058	.091	.080	.064	.075
1968	.033	.034	.037	.040	.040	.036
1969	.018	.023	.014	.040	.071	.052
1970	.056**	.036	.033	.013	.007	.029
1971	.039	.016	.026	.052	-	.029
1972	-	.016	.024	.035	.021	.024
1974	-	.002	.004	-	.017	.008
1975*	.014	.012	.007	.011	.010	.011
#	.027	.017	.017	.021	.029	.022
1976*	.012	.013	.007	.008	.006	.010
#	.016	.069	-	-	.016	.014
1977*	.023	.010	.022	.006	.018	.016
#	.030	.011	.025	-	-	.022

Note: All figures are in mg/L as P.
**One questionably high value was omitted.
Analytical Precision ± 0.003 mg/L or 10%, whichever is greater.
Standard deviations of above figures (including station and date variation) are generally 50-150% of the means.
* 4-station weekly surveys
# 8-station monthly surveys (10 stations in 1977)

TABLE 5a

t-Test of Annual Means of Phosphorus Data, Hamilton Harbour

Station	Total P			Soluble Reactive P		
	1975-76	1975-77	1976-77	1975-76	1975-77	1976-77
4	-2.04	NSD	NSD	NSD	NSD	2.36
252	NSD	NSD	NSD	NSD	NSD	2.64
258	-2.65	NSD	NSD	NSD	2.62	NSD
270	-2.64	NSD	NSD	NSD	NSD	NSD

Note: The value of "t" is indicated where significant at the 5% level.

Negative "t" indicates a significant decrease in the mean.
"NSD" = no significant difference.

TABLE 6

Outfall Areas with Highest Phosphorus Concentration, Hamilton Harbour, 1977

Location	Typical Values, mg/l as P Total P	 Soluble Reactive P
225	3.1-5.1	1.8-1.9
211	2.0-3.9	1.1-1.8
273	1.3-1.6	0.6-1.2
274	0.3-4.7	0.14-0.55

TABLE 7

Harbour-wide Monthly Means of Iron and Zinc Concentrations, 1975-1977 (mg/L)

	Iron			Zinc		
	1975	1976	1977	1975	1976	1977
Apr	0.31	0.33	0.18	0.08	0.07	0.05
May	0.19	0.33	0.40	0.08	0.06	0.05
Jun	0.22	0.19	0.28	0.02	0.14	0.09
Jul	0.34	0.46	0.35	0.08	0.10	0.05
Aug	0.26	0.27	0.26	0.07	0.06	0.03
Sep	0.37	0.38	0.20	0.03	0.06	0.04
Oct	0.26	0.16	0.35	-	0.06	-
Year	0.28	0.30	0.29	0.06	0.09	0.06

TABLE 8

Correlation Matrix of 1977 Hamilton Harbour Organic Pollution Parameters

	BOD	COD	TOC	Turbidity	SS
BOD	1.000	0.170	0.156	0.122	0.170
COD		1.000	0.080	-0.004	-0.000
TOC			1.000	0.063	0.057
Turbidity				1.000	0.823
SS					1.000

TABLE 9

Mean Values of Oxygen Demand Indicators, Hamilton Harbour, 1976-77

Location	BOD	COD	TOC	FOC
Harbour-wide (4 locations) 1976	3.6	21	5.5	4.7
Harbour-wide (4 locations) 1977	3.3	27	6.6	6.1
Outfall Areas				
82	6	26	8	7
99	4	21	7	6
103	5	35	10	7
108	8	54	13	8
121	5	35	7	5
273	30	130	90	15
250 (0.5 m depth)	4	32	6	4
250 (2 m depth)	4	30	6	3
212 (0.5 m depth)	5	29	7	5
212 (2-5 m depth)	6	26	6	5
211	60	130	70	30
220	8	40	9	8
225	140	600	1400	50
274	14	50	20	10

TABLE 10

Contribution of various ions to total conductivity, Hamilton Harbour, 1976-77

Date Y/M/D	Stn.	$CO_3^=$ A	$CO_3^=$ B	HCO_3^- A	HCO_3^- B	$SO_4^=$ A	$SO_4^=$ B	Cl^- A	Cl^- B	NO_3^- A	NO_3^- B	Ca^{++} A	Ca^{++} B	Mg^{++} A	Mg^{++} B	Na^+ A	Na^+ B	K^+ A	K^+ B	NH_4^+ A	NH_4^+ B	Σ Anions meq/l	Σ Cations meq/l	Conduct. (umho/cm) Calc.	Conduct. (umho/cm) Obs.
76/11/09	4S	0.4	1	120	78	51	75	55	105	8.9	9	45	118	11	41	26	50	4.4	7	1.9	7	4.74	4.48	491	495
	4B	0.4	1	118	76	49	72	52	99	8.1	8	44	115	10	41	24	46	3.9	7	1.2	5	4.56	4.28	471	465
	252S	0.5	1	118	76	48	71	51	97	9.3	9	45	117	11	41	23	45	4.1	7	0.5	2	4.53	4.25	467	465
	252B	0.5	1	119	76	48	71	51	97	9.3	9	44	117	11	41	23	45	4.1	7	0.6	2	4.56	4.26	468	465
	258S	0.6	1	118	76	47	69	52	99	9.3	9	45	117	11	41	23	45	4.2	7	0.6	2	4.54	4.26	468	465
	258B	0.4	1	118	76	48	71	51	97	9.3	9	44	117	11	41	24	46	4.1	7	0.6	2	4.53	4.28	468	465
	270S	0.3	1	120	78	48	71	51	97	9.3	9	45	117	10	41	23	44	4.1	7	0.5	2	4.57	4.23	467	465
	270B	0.4	1	119	77	47	69	50	95	9.3	9	45	119	11	42	23	45	4.0	7	0.5	2	4.50	4.29	466	465
77/05/11	4S	0.8	2	138	89	50	73	72	136	5.8	6	52	136	11	44	39	75	6.3	10	6.9	26	5.46	5.79	597	590
	4B	0.8	2	139	90	52	76	65	123	3.7	4	50	131	11	42	32	61	4.9	8	4.3	16	5.29	5.17	553	570
	252S	1.2	3	140	89	66	96	72	135	4.1	4	52	135	11	44	37	70	6.0	10	5.6	21	5.81	5.63	608	620
	252B	1.0	2	144	92	62	90	70	132	4.1	4	52	135	11	44	35	67	5.3	9	4.5	17	5.73	5.47	592	590
	258S	1.3	3	143	91	60	87	72	136	4.4	4	52	135	12	46	34	65	5.4	9	5.0	19	5.73	5.49	595	590
	258B	0.9	2	143	91	60	87	65	122	3.7	4	53	138	12	46	34	65	5.3	9	4.3	16	5.52	5.50	580	590
	270S	2.0	5	142	91	45	66	70	133	5.1	5	53	138	12	46	34	65	5.4	9	4.0	15	5.39	5.49	574	590
	270B	0.7	2	146	94	47	69	68	129	4.5	5	52	136	12	46	34	65	5.3	9	5.0	19	5.39	5.50	573	590
77/10/13	4S	0.3	1	137	88	53	77	50	95	9.6	10	51	133	10	38	25	48	4.3	7	0.7	3	4.92	4.61	500	485
	4B	0.3	1	132	85	48	70	45	86	8.5	9	49	129	10	37	21	40	3.8	6	0.3	1	4.58	4.25	464	446
	252S	0.3	1	132	85	50	73	48	91	9.9	10	50	131	10	39	24	46	4.2	7	0.3	1	4.73	4.49	484	470
	252B	0.3	1	132	85	50	73	49	92	10.0	10	50	131	10	39	24	46	4.1	7	0.3	1	4.74	4.49	485	468
	258S	0.2	1	132	85	55	80	47	89	10.5	11	50	131	10	38	23	44	4.1	7	0.3	1	4.81	4.44	487	466
	258B	0.3	1	127	82	53	78	47	88	9.6	10	49	128	10	38	23	44	4.0	7	0.4	1	4.66	4.39	477	460
	270S	0.3	1	137	88	63	92	47	89	10.2	10	50	130	10	38	23	44	4.1	7	0.3	1	5.06	4.44	499	465
	270B	0.3	1	137	88	53	78	47	88	9.7	10	50	131	10	38	23	44	4.1	7	0.2	1	4.82	4.43	485	466

Note: Columns "A" are concentrations in mg/l of each ion as stated.
Columns "B" are ionic contributions to conductivity in umho/cm.
"S" is surface (0.2 m depth)
"B" is bottom (18 m at St. 4, 6 m at St. 252, 20 m at St. 258, 12 m at St. 270)

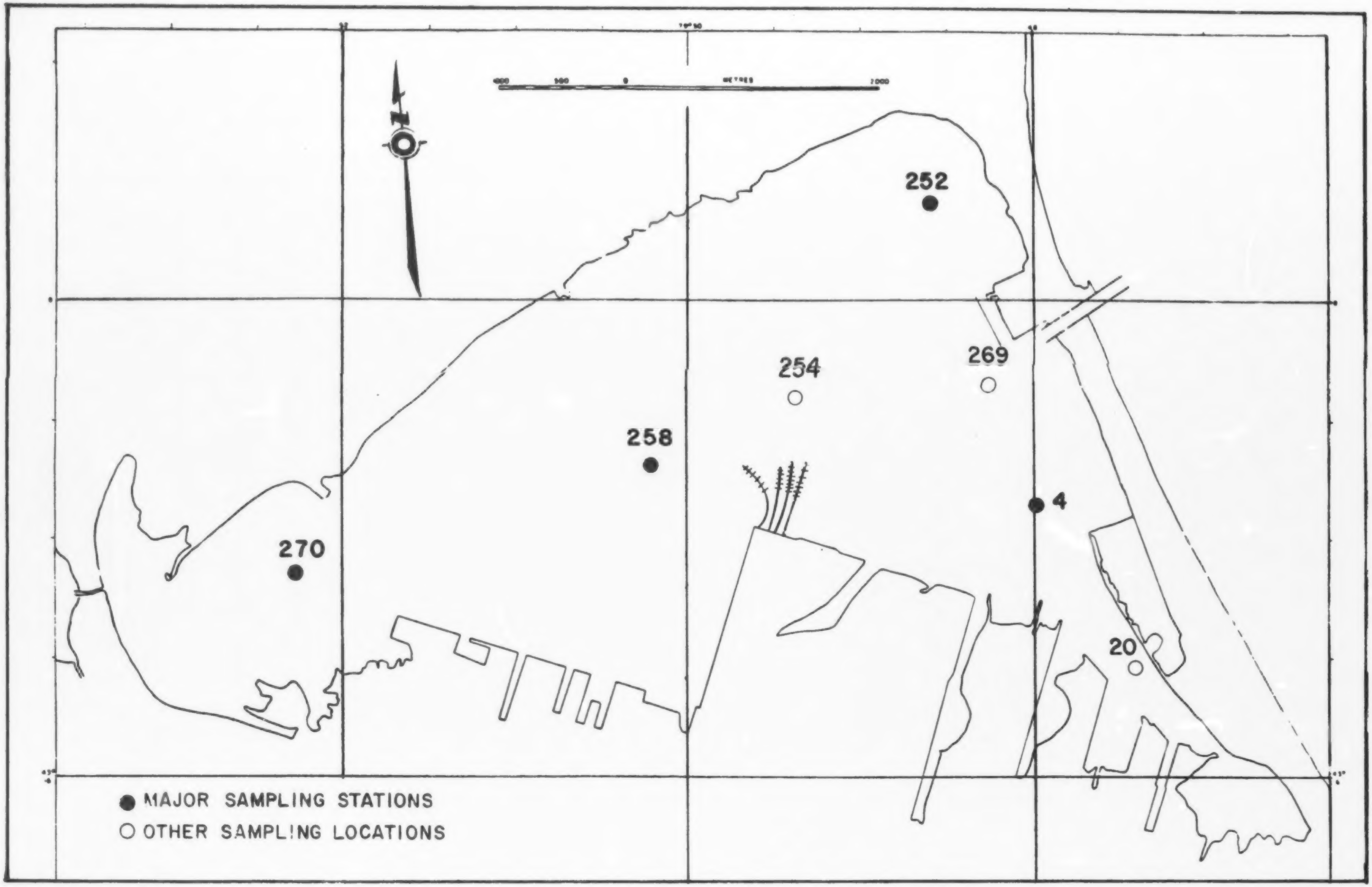
1000
500
0
METRES
2000
252
269
254
258
4
270
20
● MAJOR SAMPLING STATIONS
○ OTHER SAMPLING LOCATIONS

FIGURE 1: HAMILTON HARBOUR ILLUSTRATING DIFFUSER LINE, AND MAJOR SAMPLING STATIONS

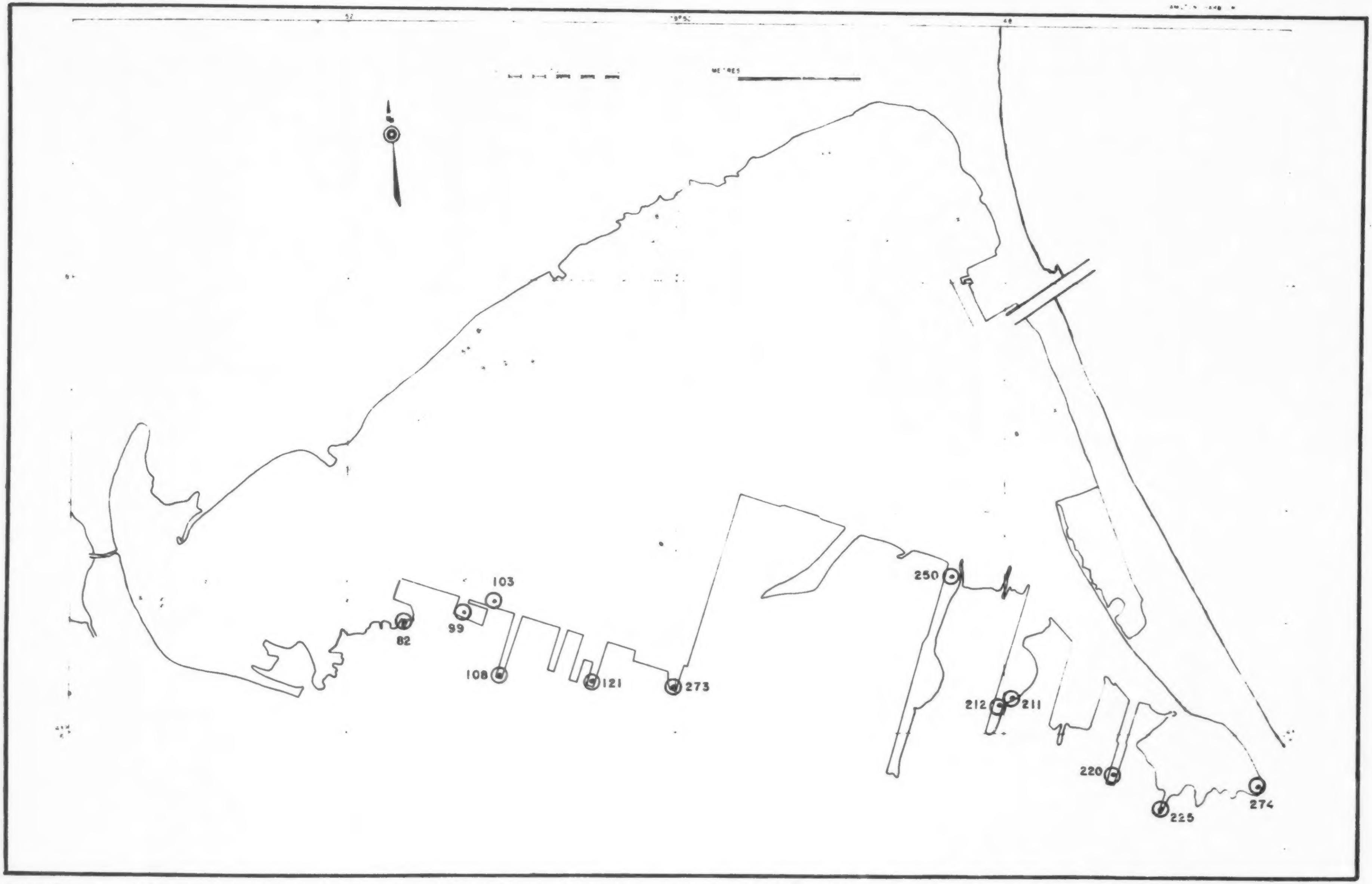
METRES
103
82
99
108
121
273
250
212
211
220
225
274

FIGURE 1a: LOCATIONS OF STORM AND INDUSTRIAL OUTFALL RUNOFF SAMPLING POINTS, HAMILTON HARBOUR, 1977

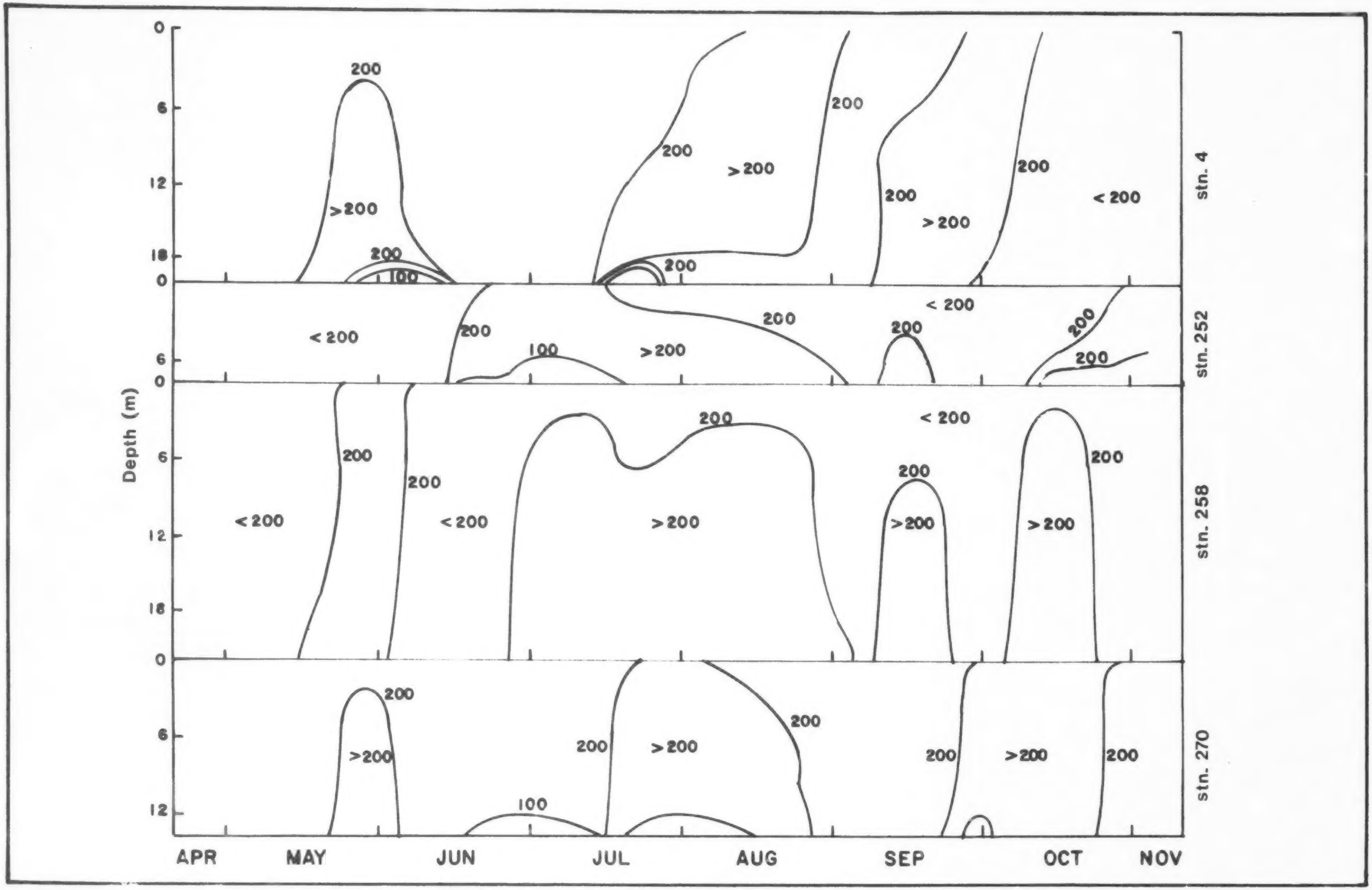

FIGURE 2 · ISOPLETHS OF APPARENT REDOX POTENTIALS (mv) AT FOUR MAJOR SAMPLING STATIONS. HAMILTON HARBOUR 1976

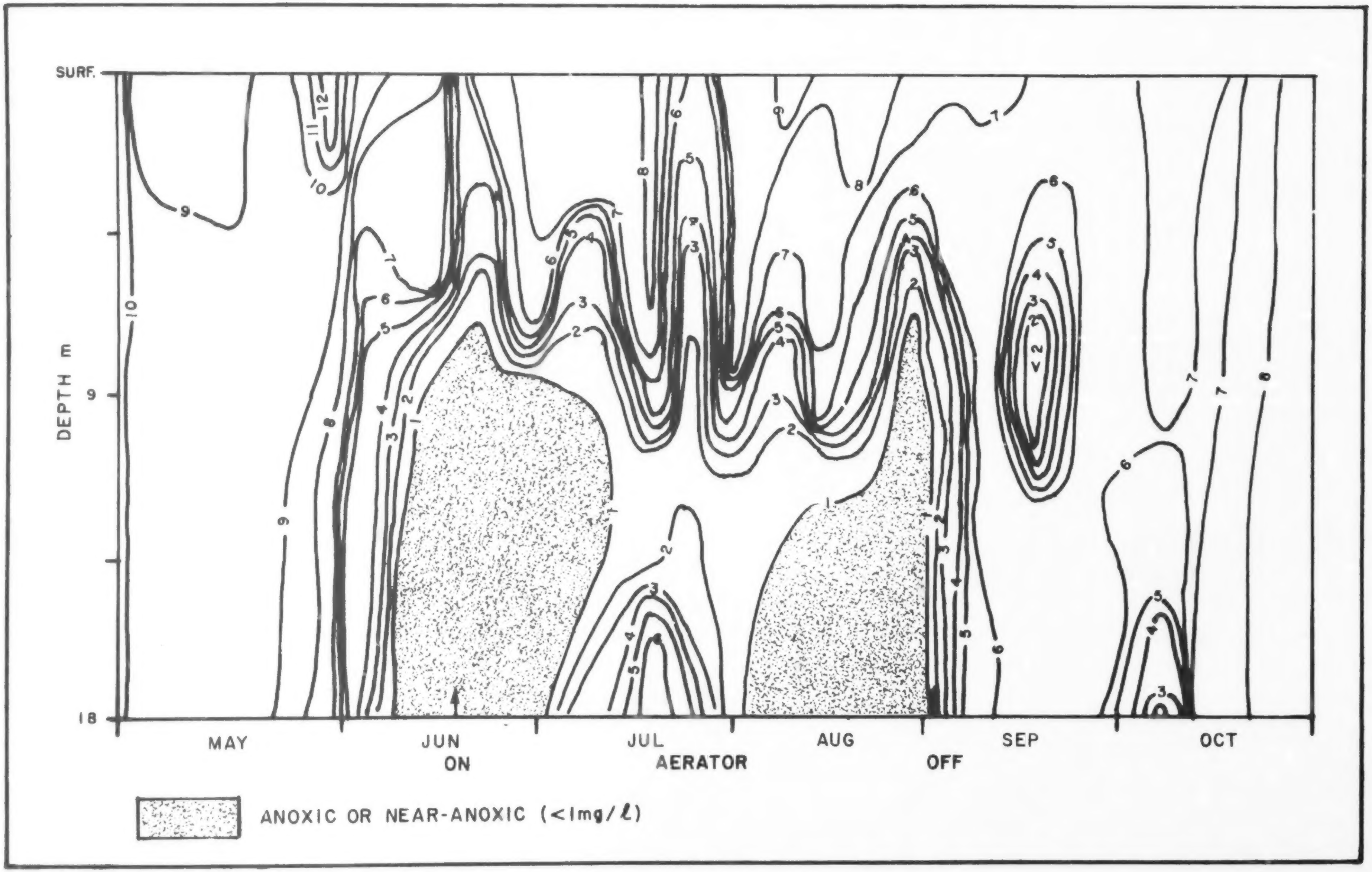

FIGURE 3a : DISSOLVED OXYGEN PROFILES (mg/ℓ) HAMILTON HARBOUR 1976, STATION 4.

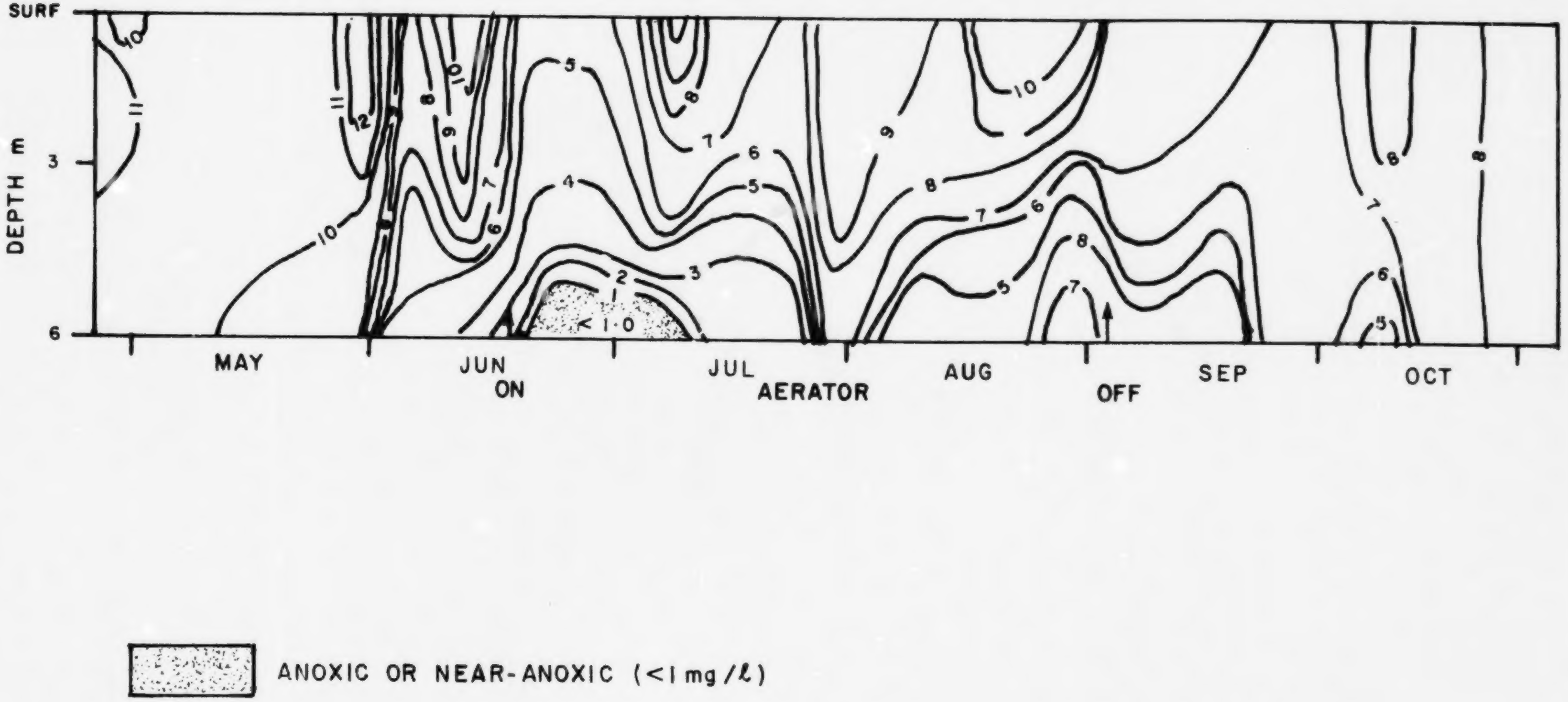

FIGURE 3b: DISSOLVED OXYGEN PROFILES (mg/ℓ) HAMILTON HARBOUR 1976 STATION 252

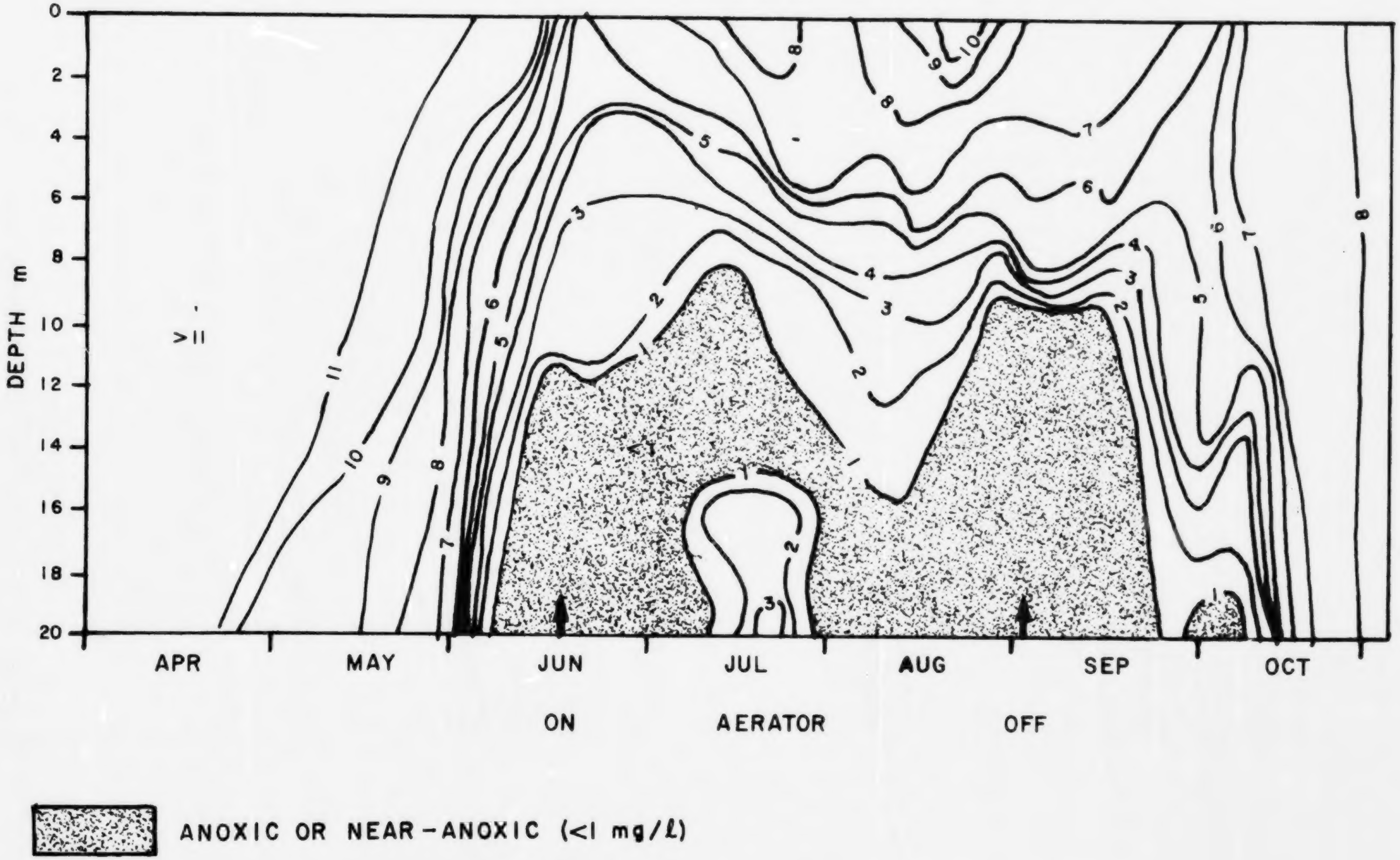

FIGURE 3c : DISSOLVED OXYGEN PROFILES (mg/ℓ). HAMILTON HARBOUR 1976 STATION 258.

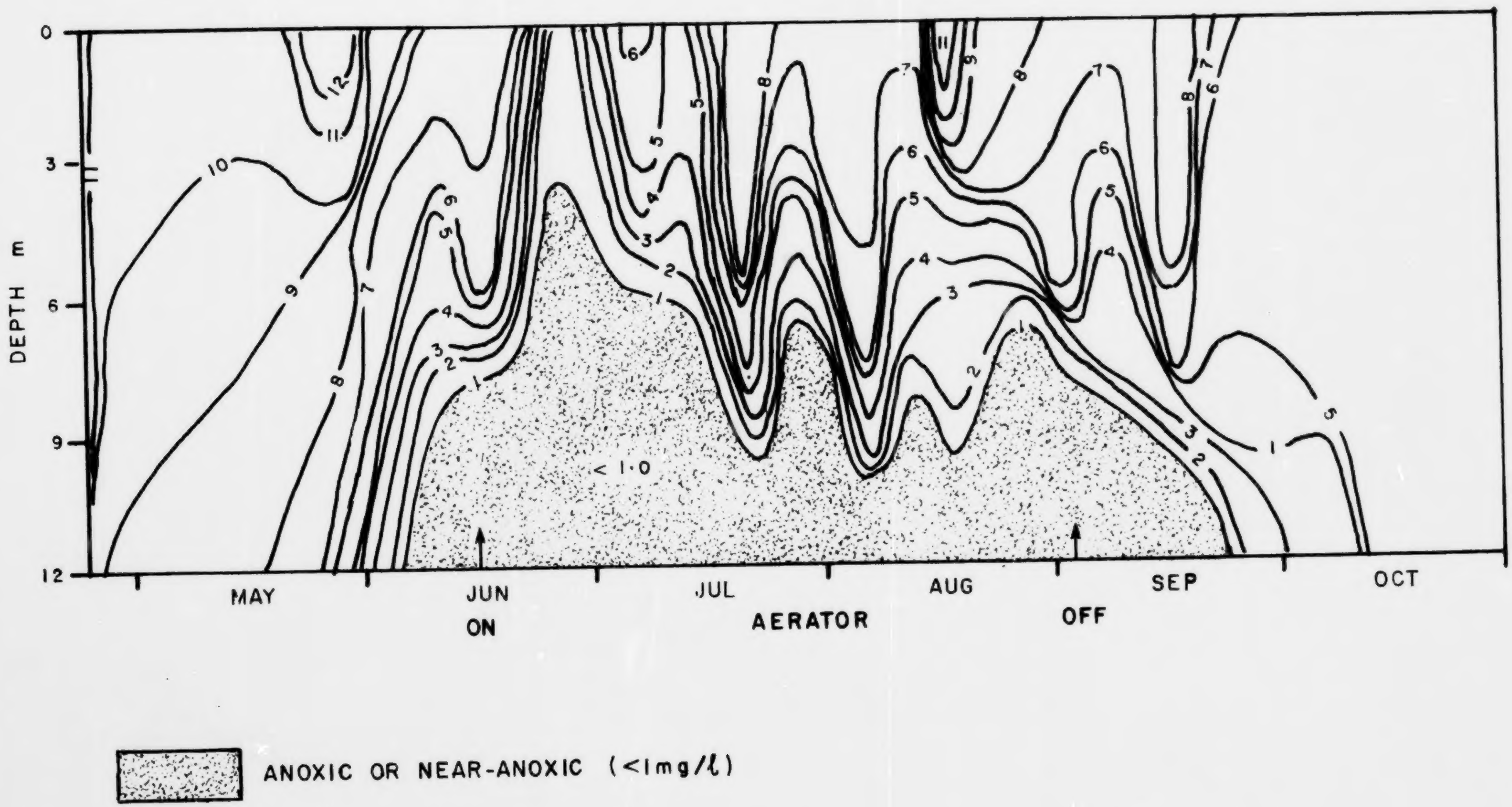

FIGURE 3d: DISSOLVED OXYGEN PROFILES (mg/ℓ), HAMILTON HARBOUR 1976 STATION 270

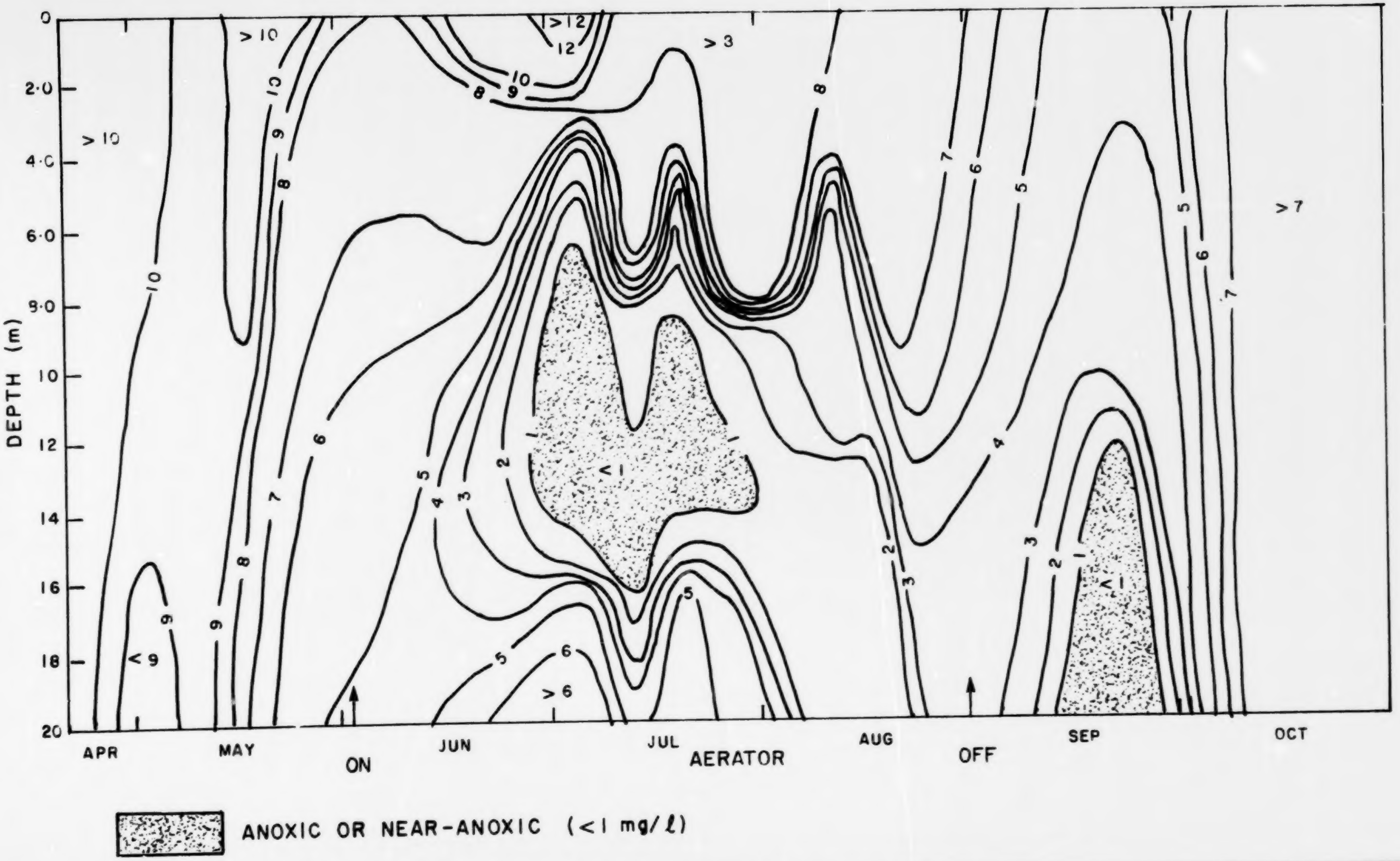

FIGURE 4(a): DISSOLVED OXYGEN PROFILES (mg/ℓ), HAMILTON HARBOUR, 1977, STATION 4

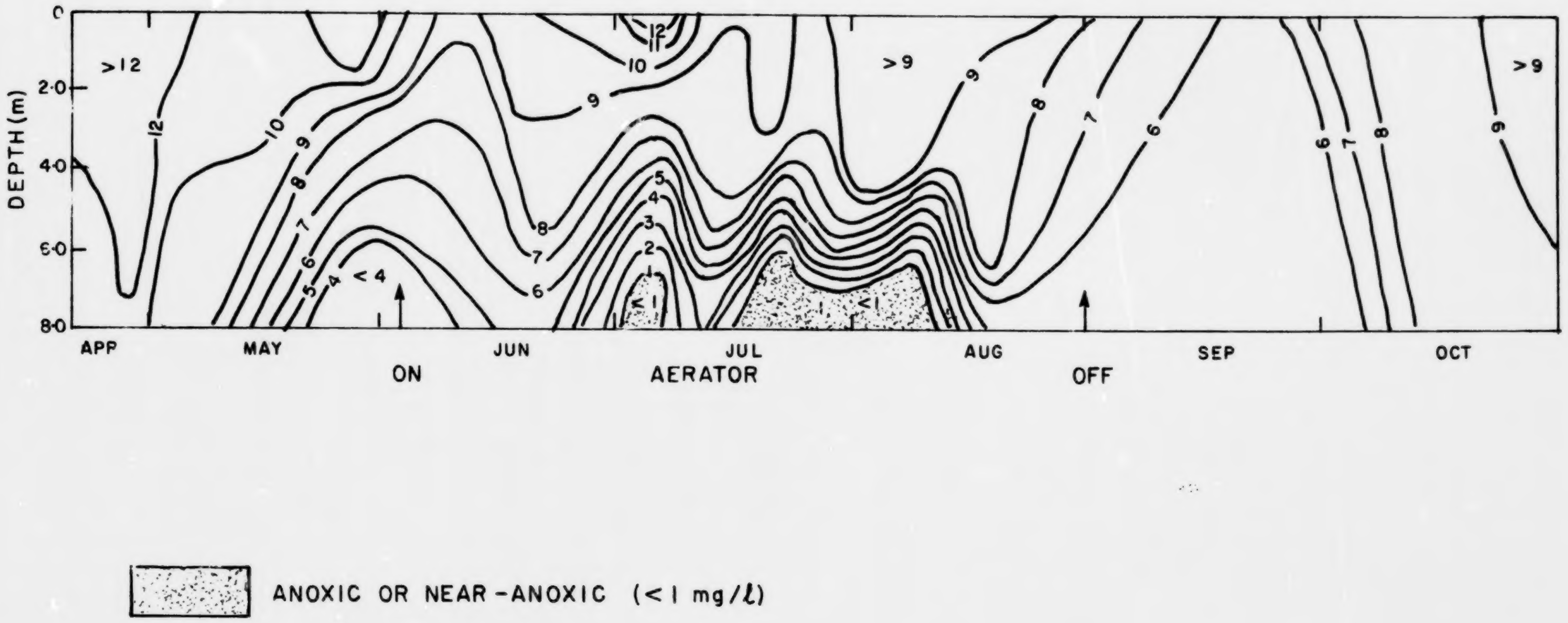

FIGURE 4(b) : DISSOLVED OXYGEN PROFILES, HAMILTON HARBOUR, 1977, STATION 252

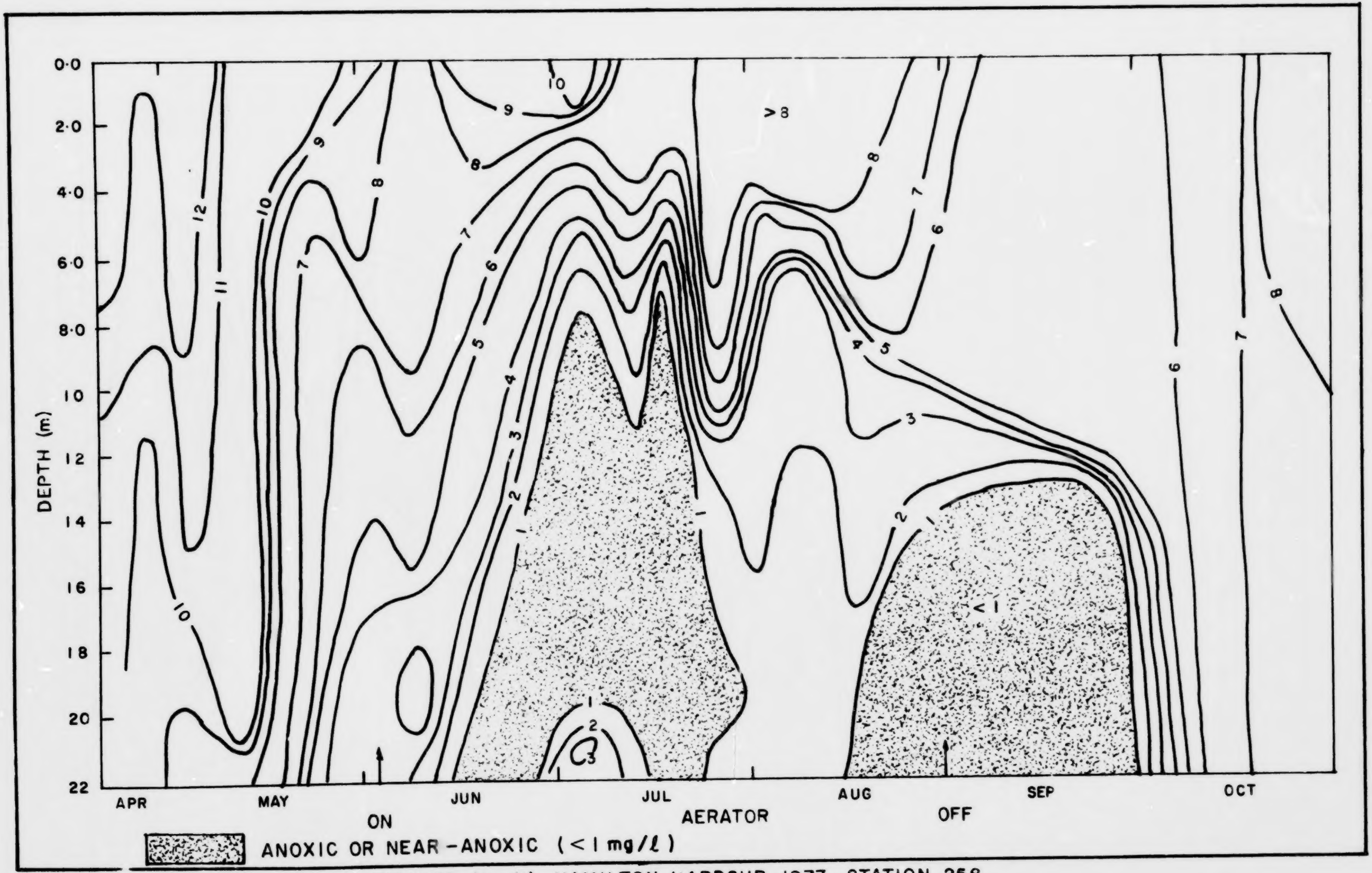

FIGURE 4c: DISSOLVED OXYGEN PROFILES (mg/ℓ), HAMILTON HARBOUR, 1977, STATION 258

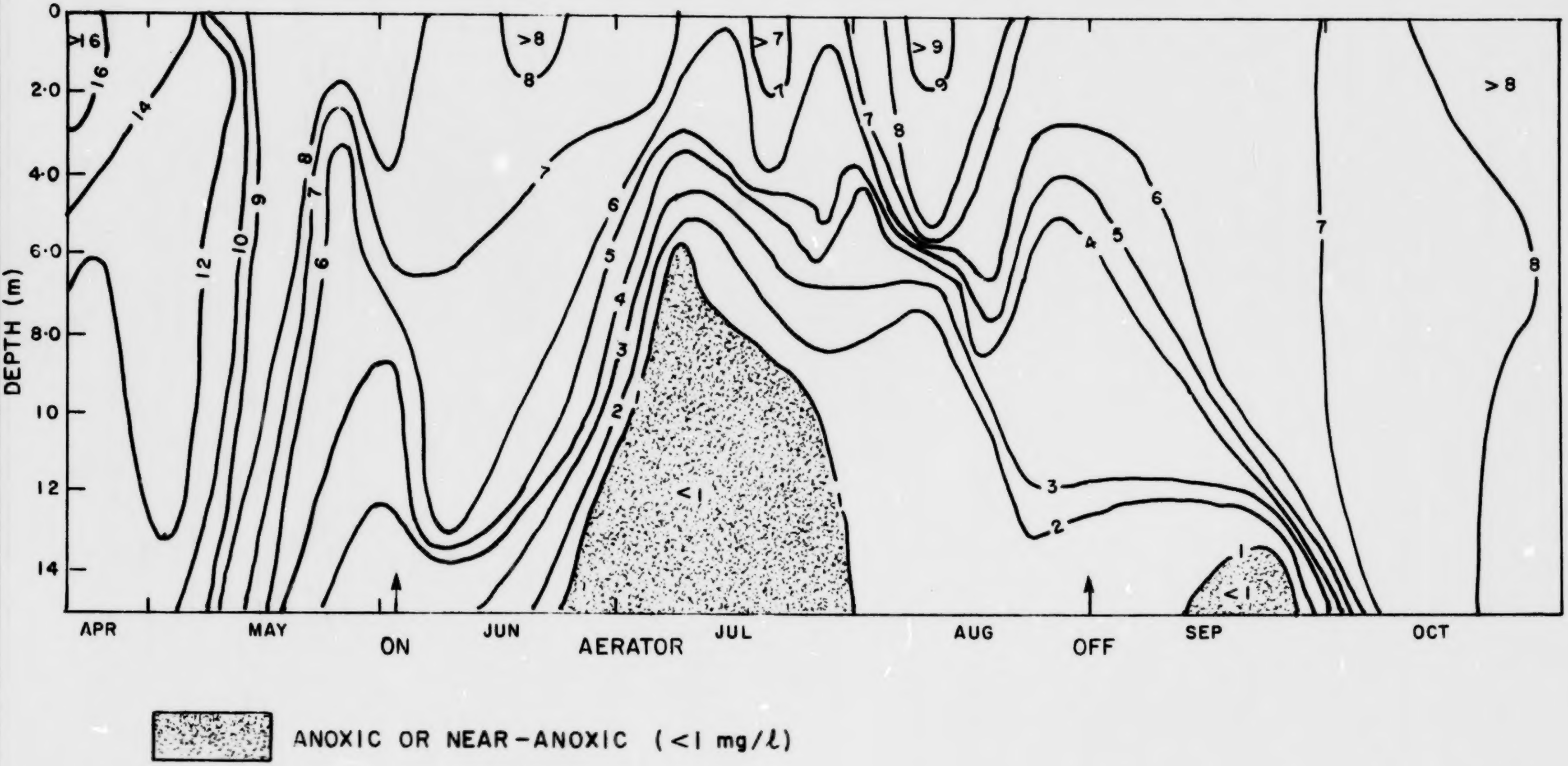

FIGURE 4 (d) : DISSOLVED OXYGEN PROFILES, HAMILTON HARBOUR, 1977, STATION 270

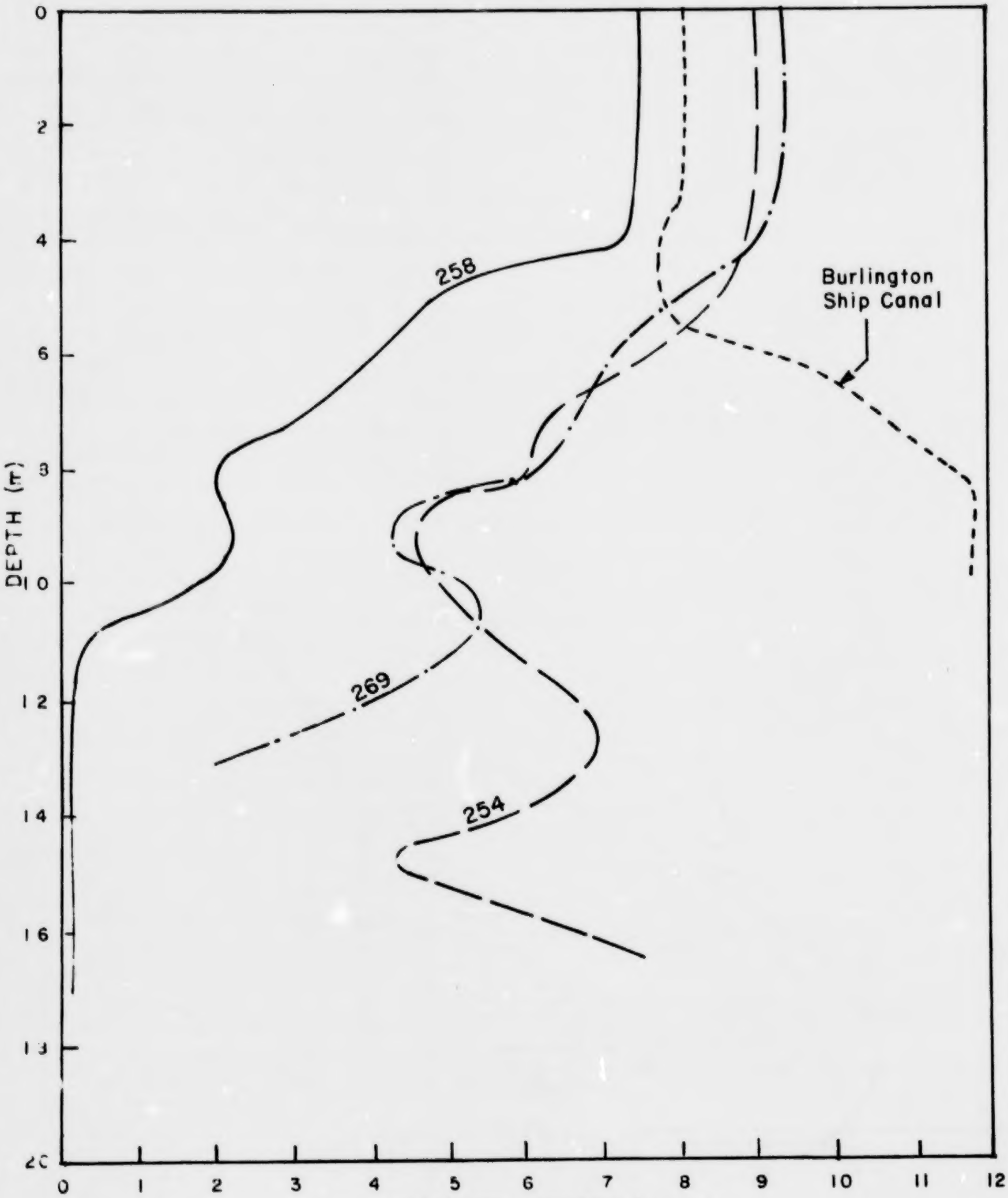

FIGURE 5: DISSOLVED OXYGEN – DEPTH PROFILES, HAMILTON HARBOUR AND BURLINGTON SHIP CANAL, JULY 13, 1977 EAST TO CENTRAL HARBOUR: CANAL, 269, 254, 258

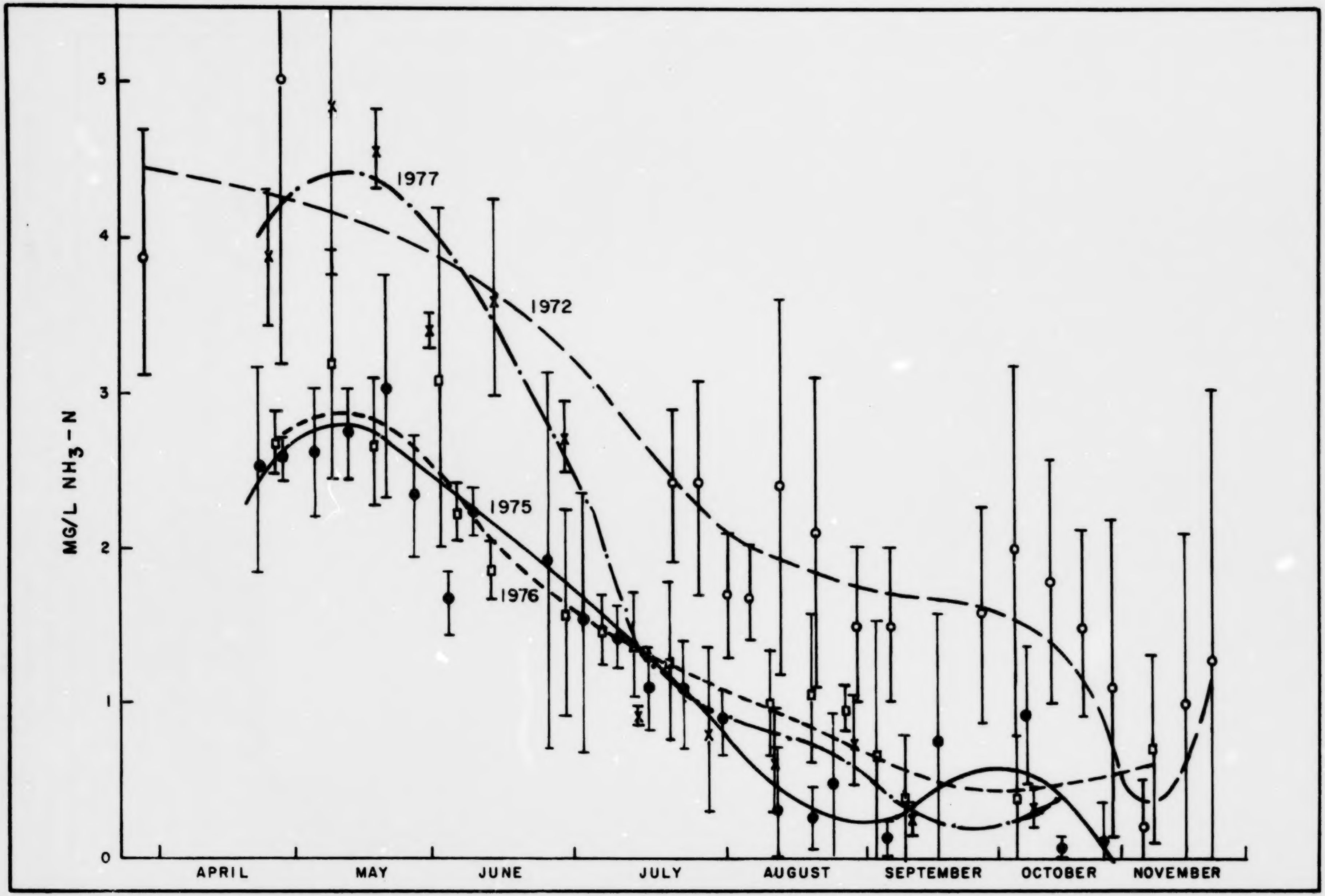

FIGURE 6: SEASONAL TRENDS OF AMMONIA IN 1972, 1975, 1976 AND 1977

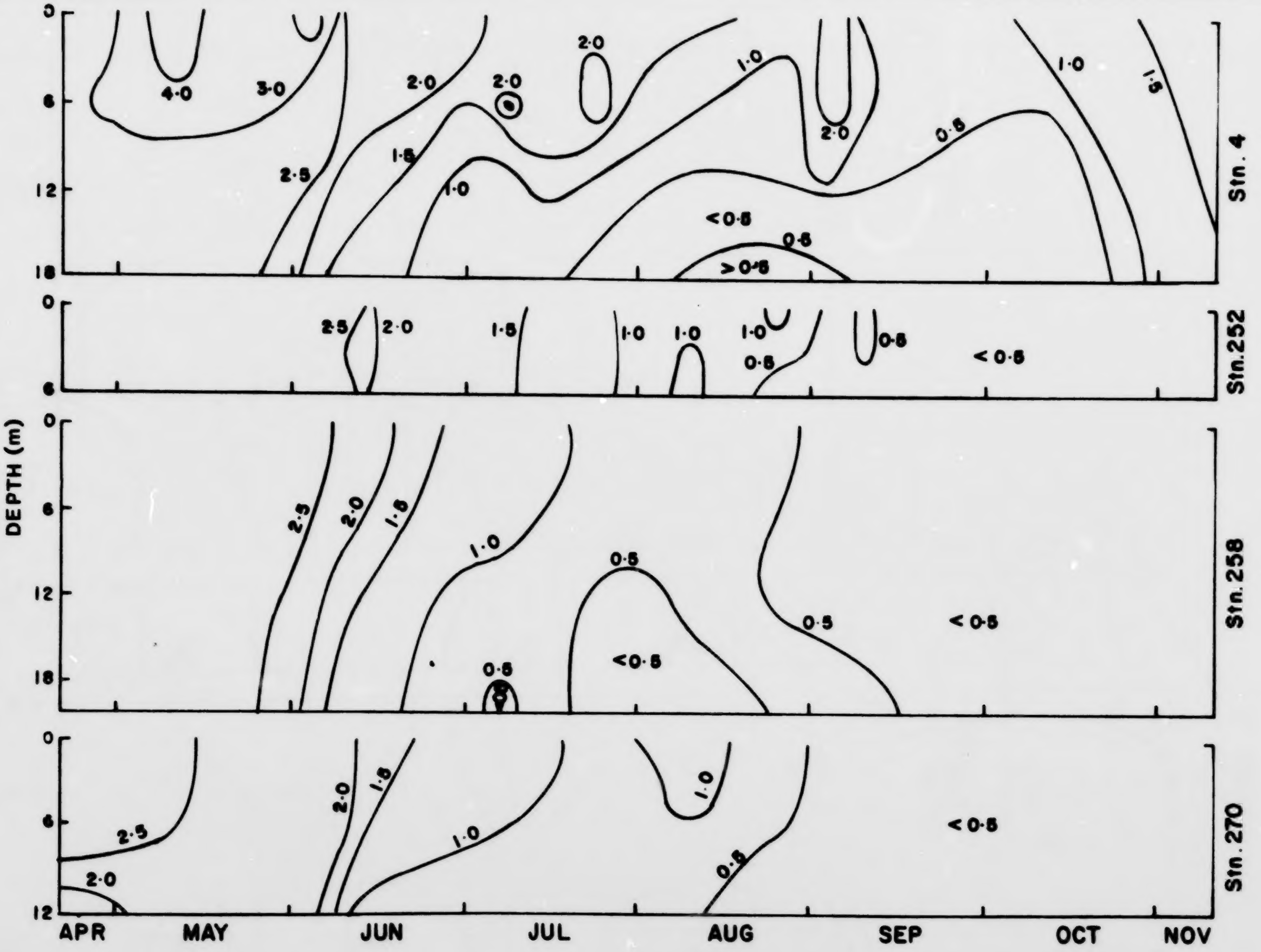

FIGURE 7 : ISOPLETHS OF NH_3 (mg/ℓ) AT MAJOR SAMPLING STATIONS. HAMILTON HARBOUR 1976

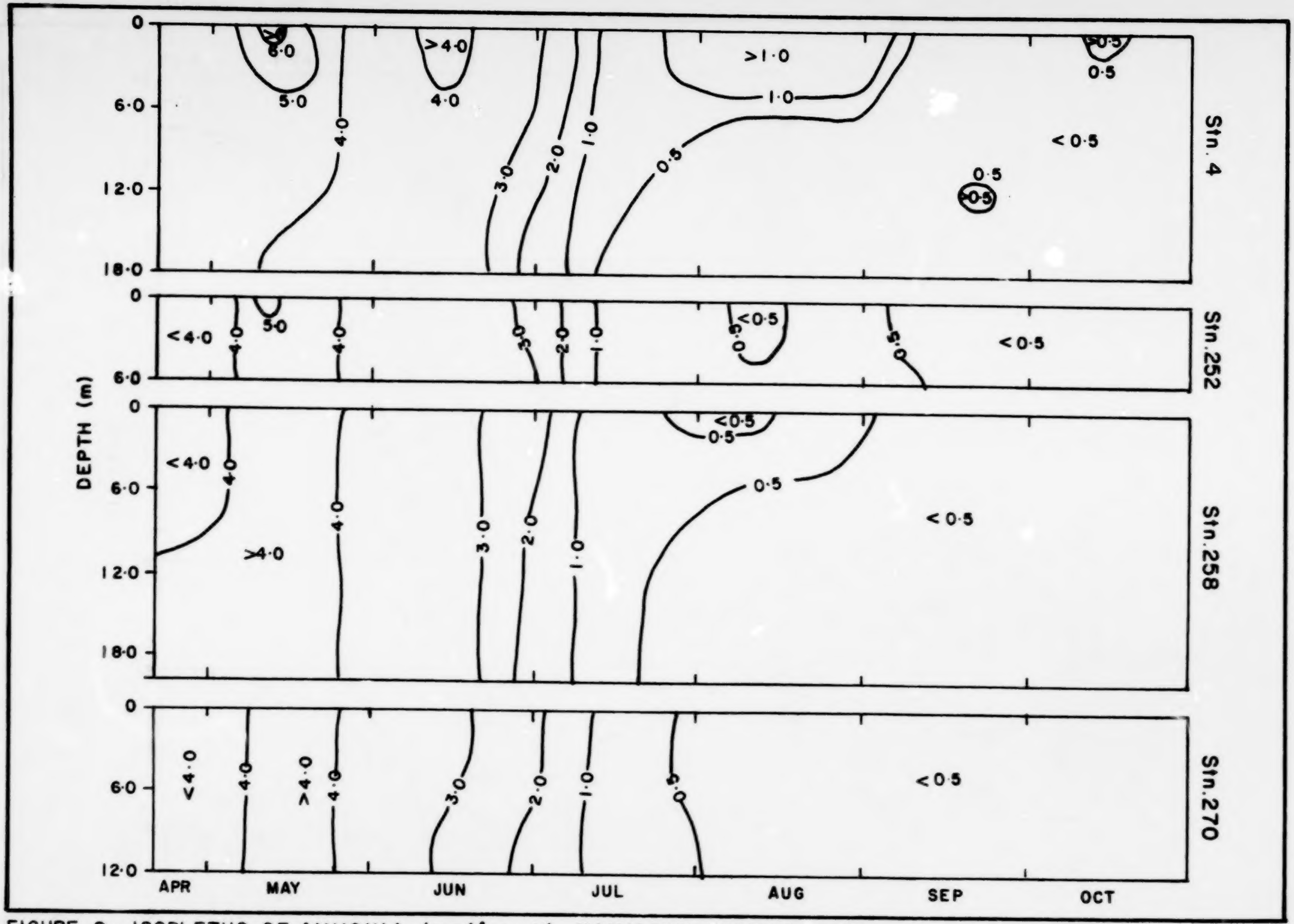

FIGURE 8 : ISOPLETHS OF AMMONIA (mg/ℓ as N), HAMILTON HARBOUR, 1977

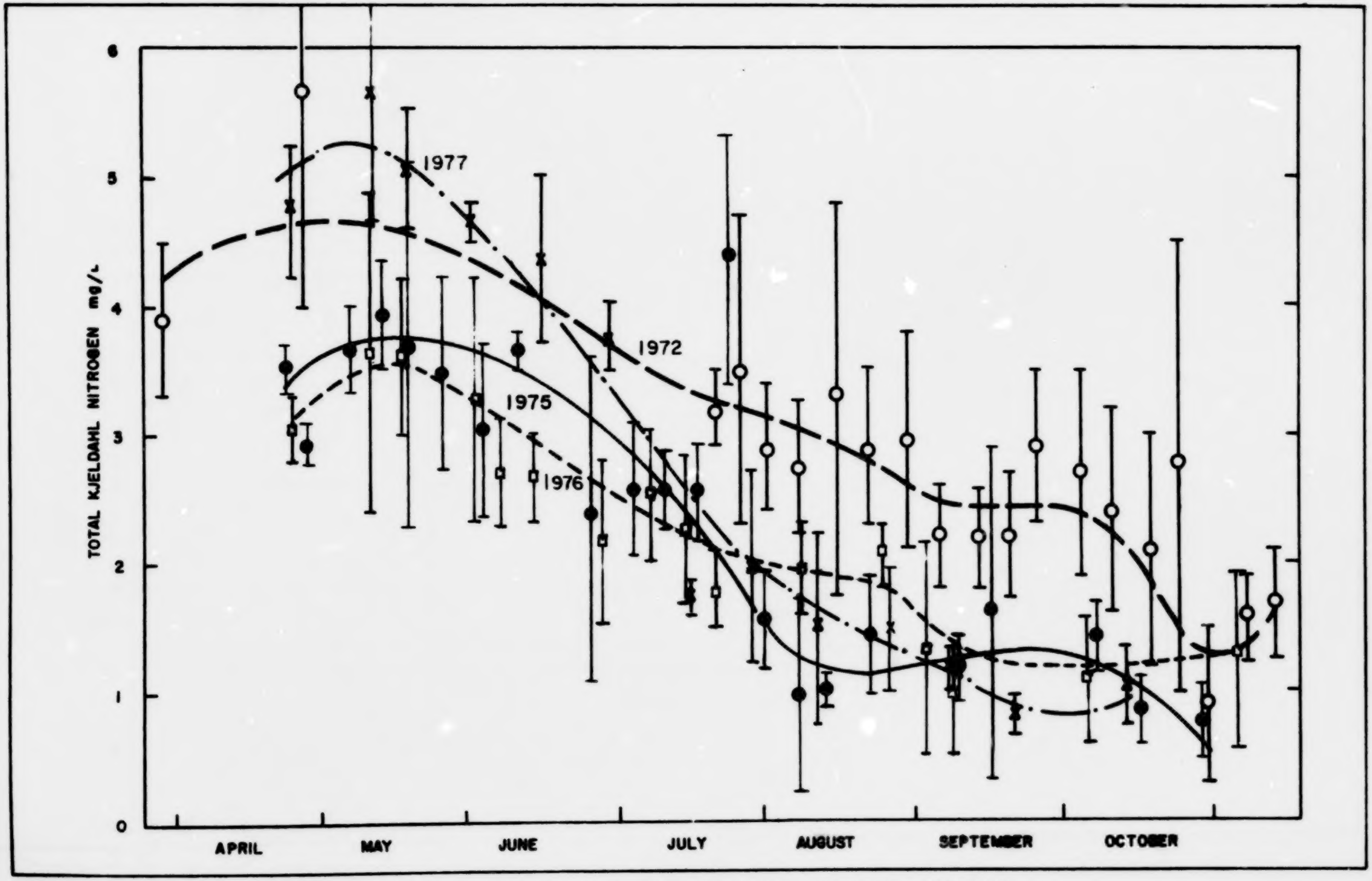

FIGURE 9 : SEASONAL TRENDS OF TOTAL KJELDAHL NITROGEN IN 1972, 1975, 1976 AND 1977

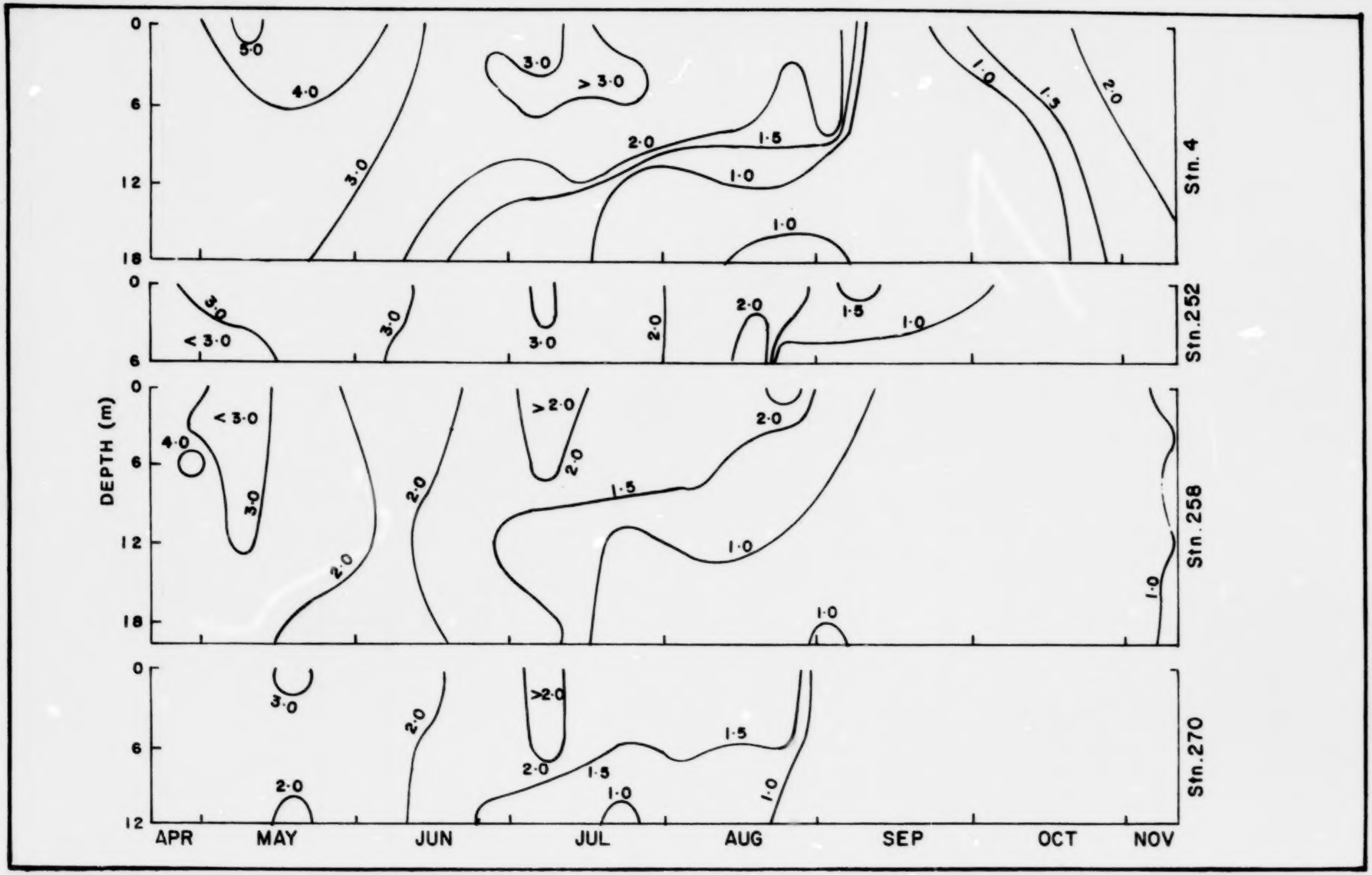

FIGURE 10: ISOPLETHS OF TOTAL KJELDAHL NITROGEN (mg/l) AT MAJOR SAMPLING STATIONS. HAMILTON HARBOUR 1976.

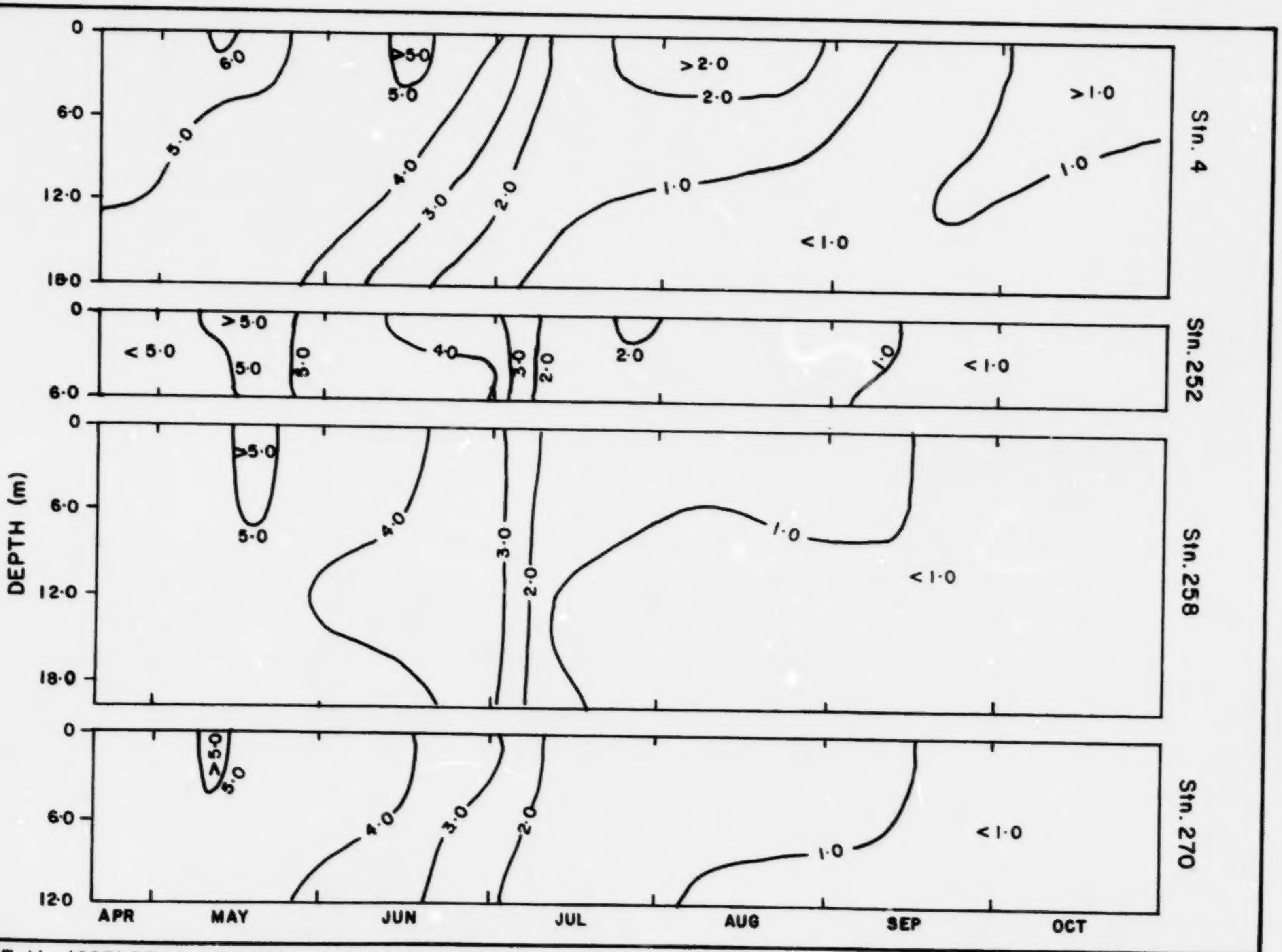

FIGURE 11 : ISOPLETHS OF TOTAL KJELDAHL NITROGEN (mg/ℓ as N), HAMILTON HARBOUR, 1977

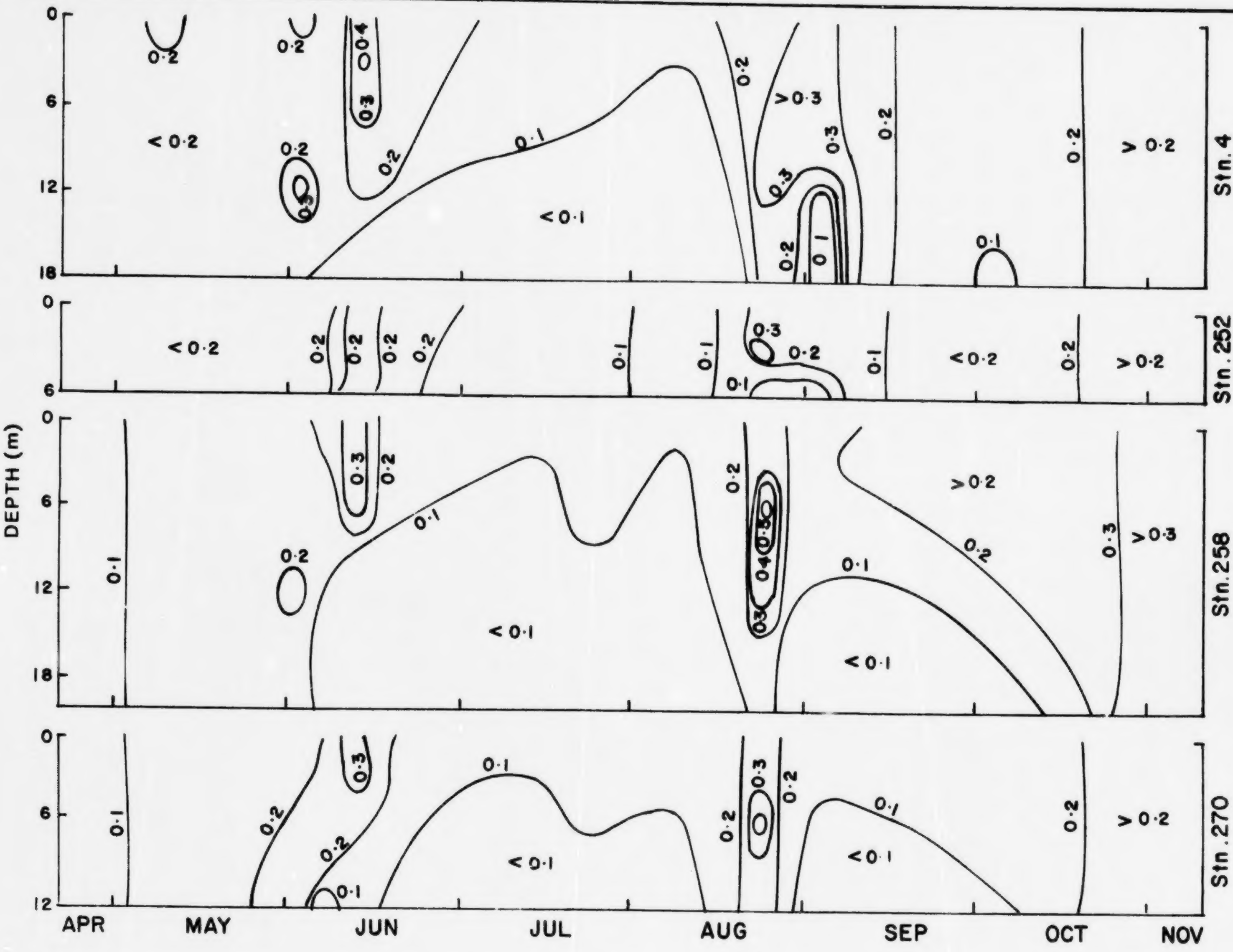

FIGURE 12 : ISOPLETHS OF NITRITE mg/ℓ AT MAJOR SAMPLING STATIONS. HAMILTON HARBOUR 1976

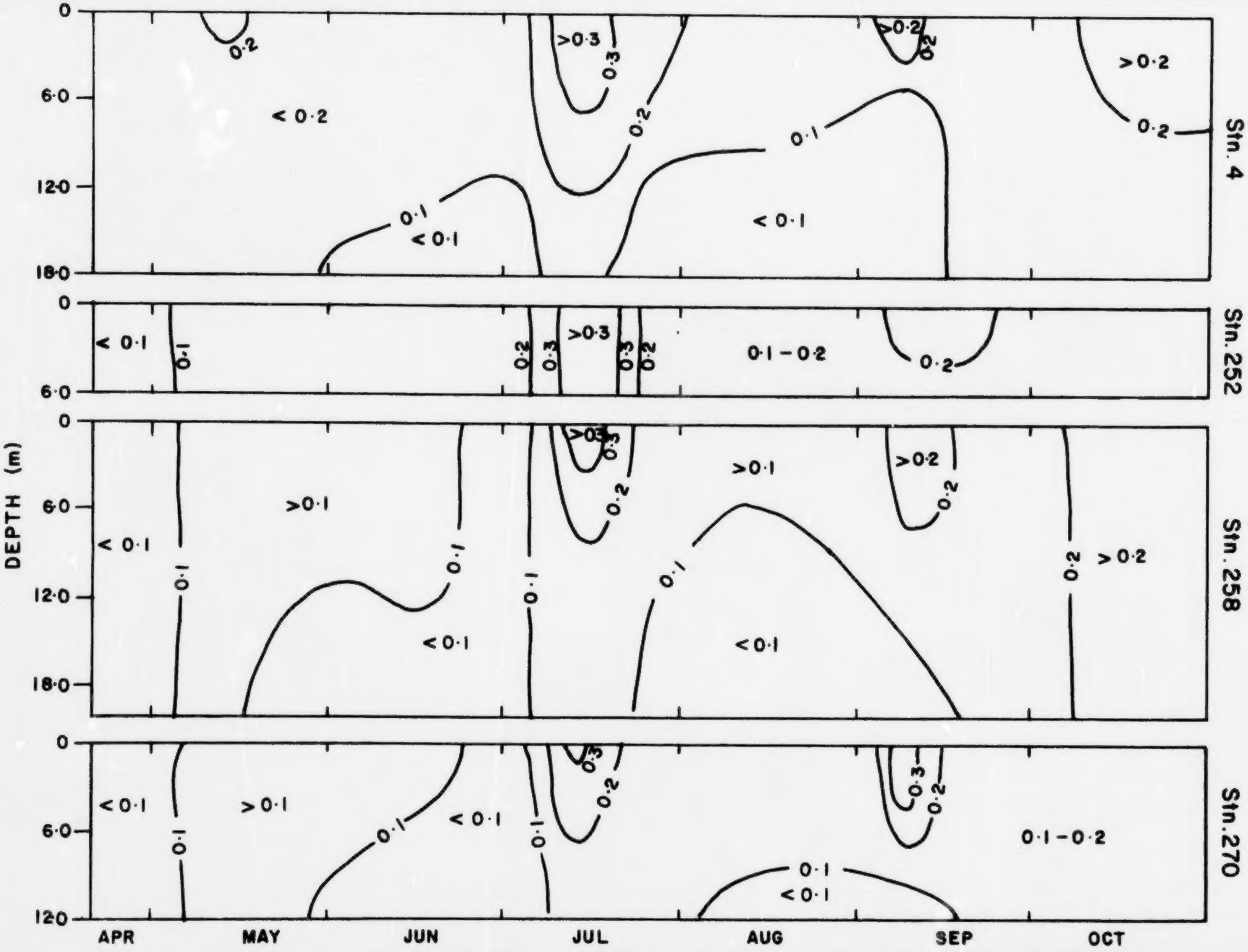

FIGURE 13 : ISOPLETHS OF NITRITE (mg/ℓ as N), HAMILTON HARBOUR, 1977

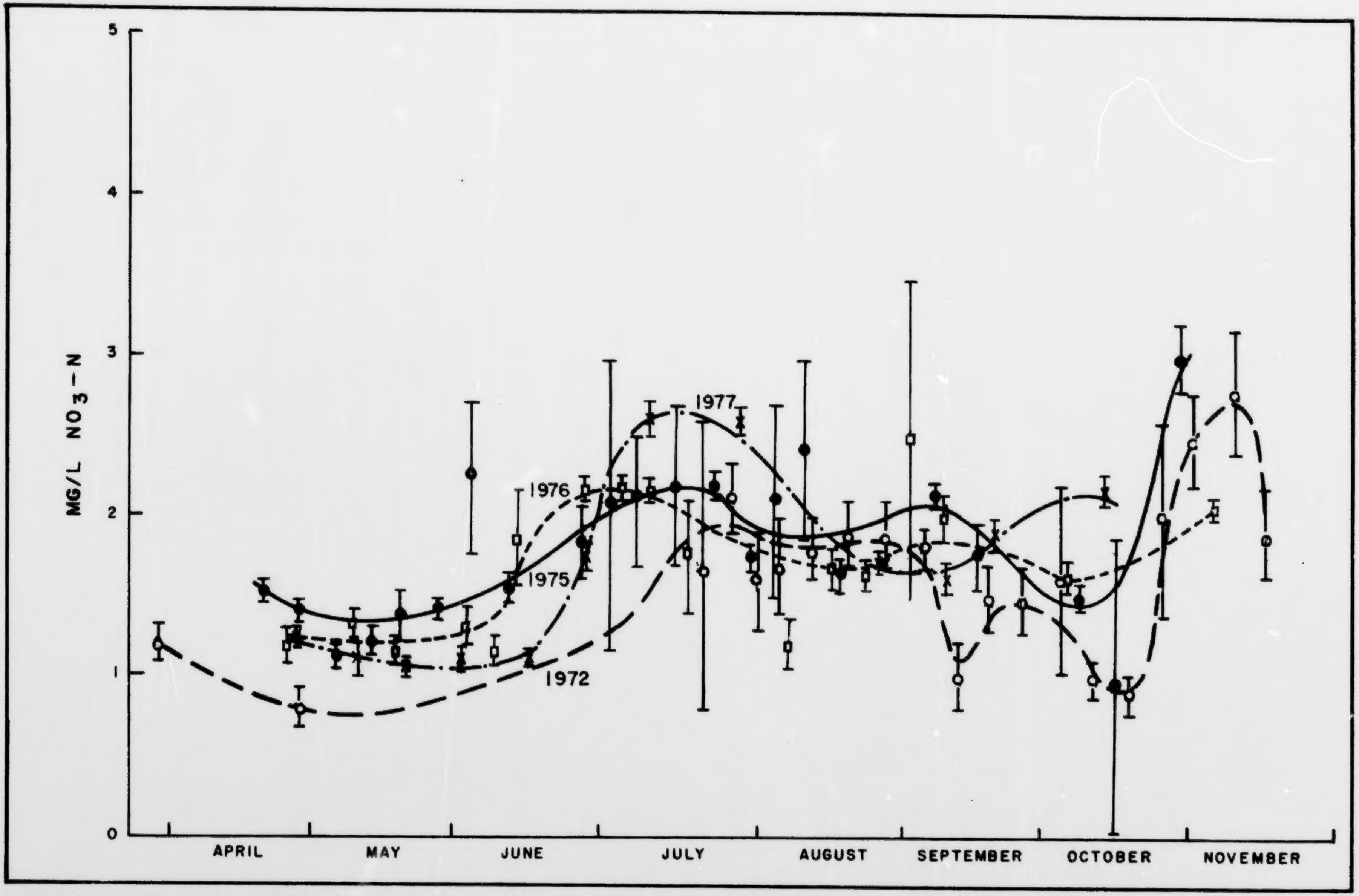

FIGURE 14: SEASONAL TRENDS OF NITRATE IN 1972, 1975, 1976 AND 1977

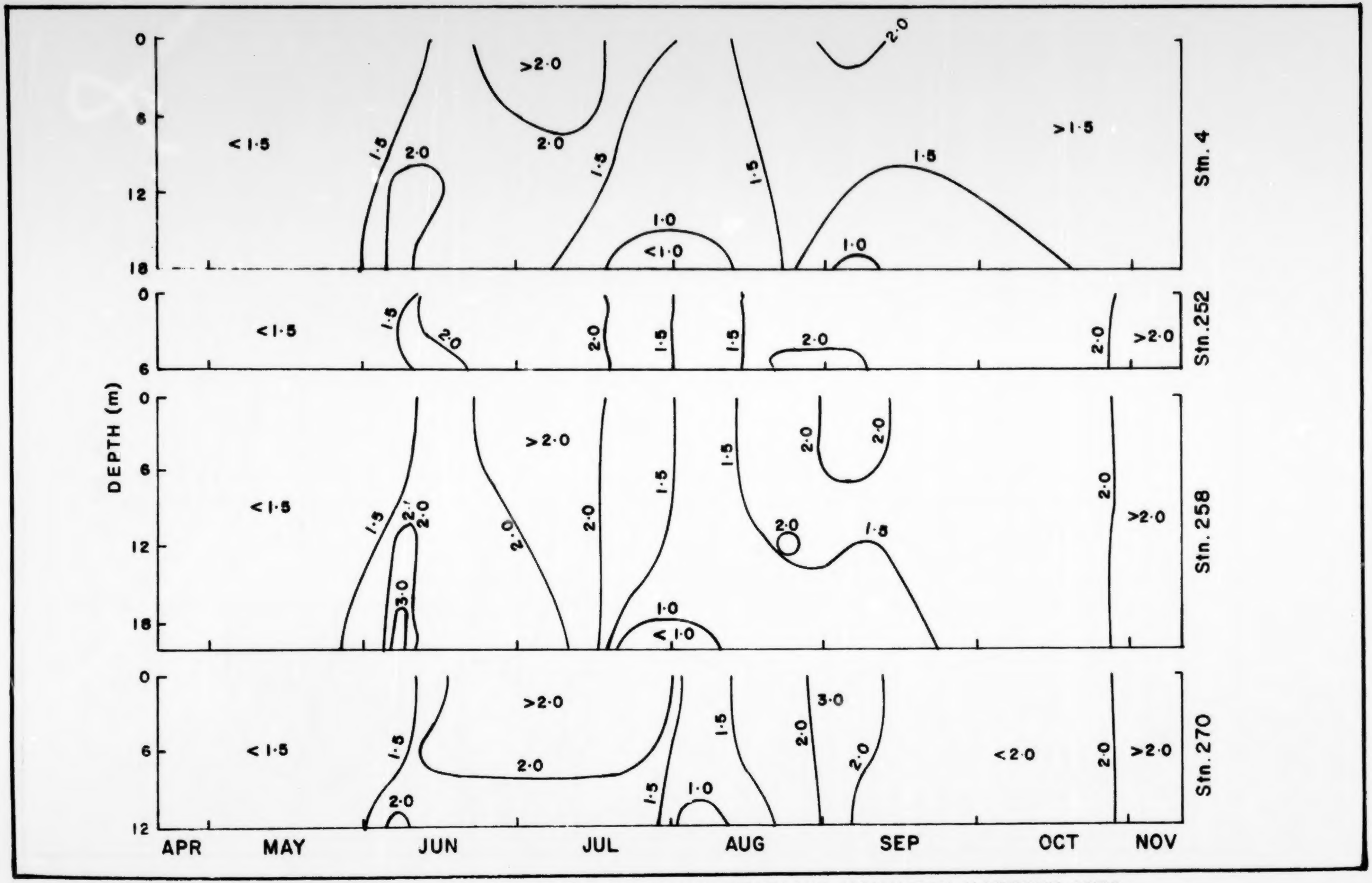

FIGURE 15: ISOPLETHS OF NITRATE (mg/ℓ) AT MAJOR SAMPLING STATIONS. HAMILTON HARBOUR 1976

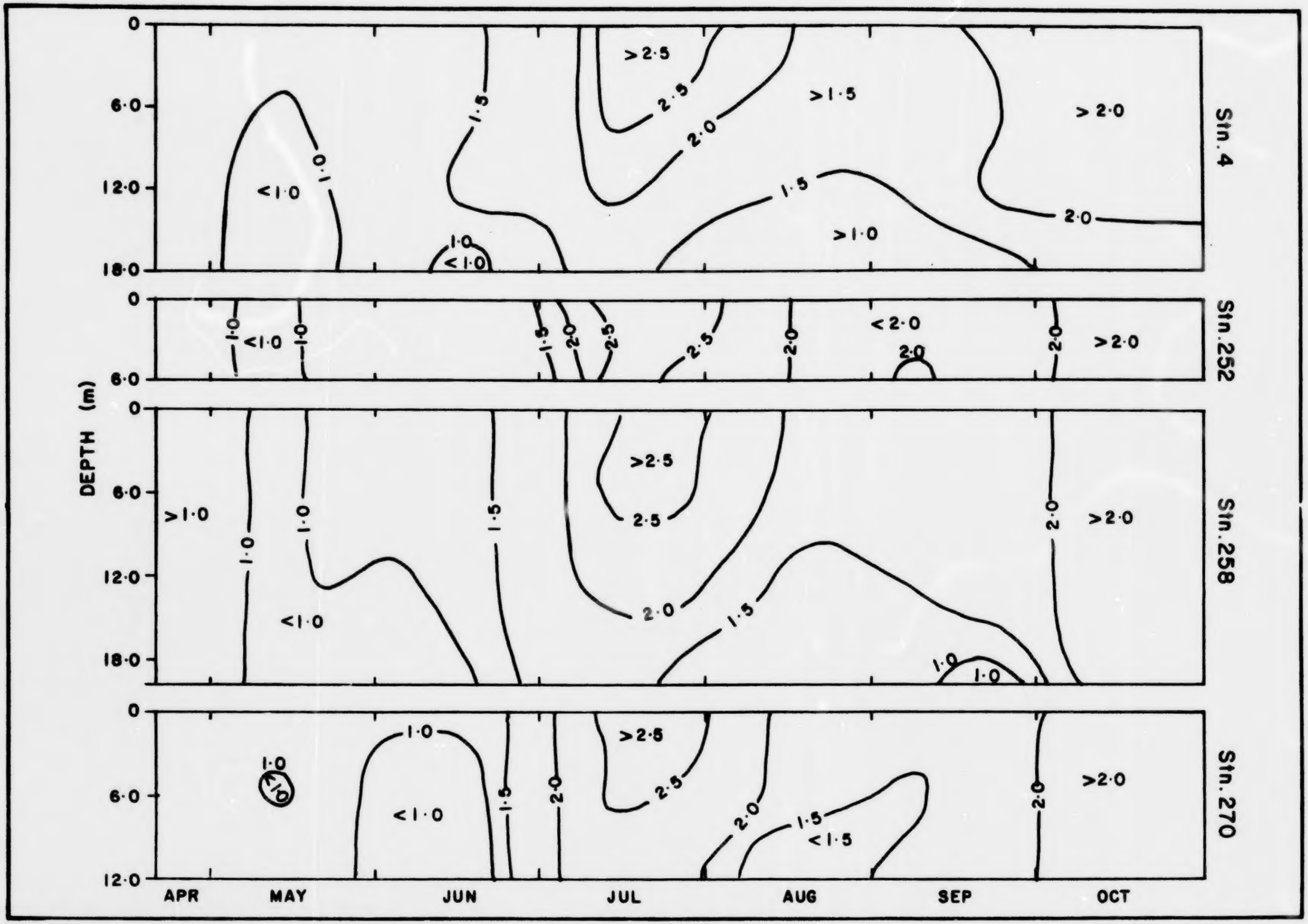

FIGURE 16 : ISOPLETHS OF NITRATE (mg/ℓ as N), HAMILTON HARBOUR, 1977

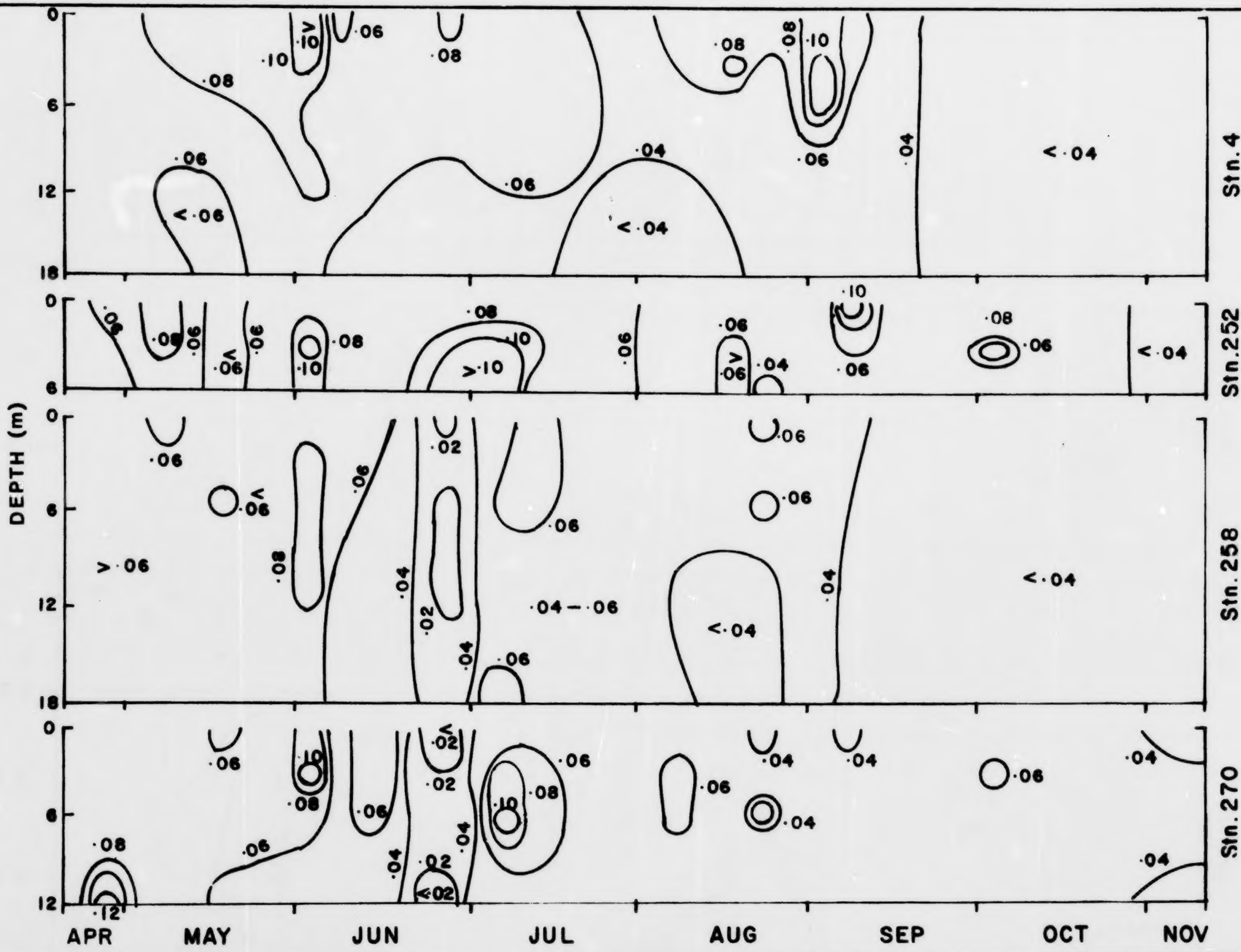

FIGURE 17: ISOPLETHS OF TOTAL PHOSPHORUS mg/ℓ AT MAJOR SAMPLING STATIONS. HAMILTON HARBOUR 1976.

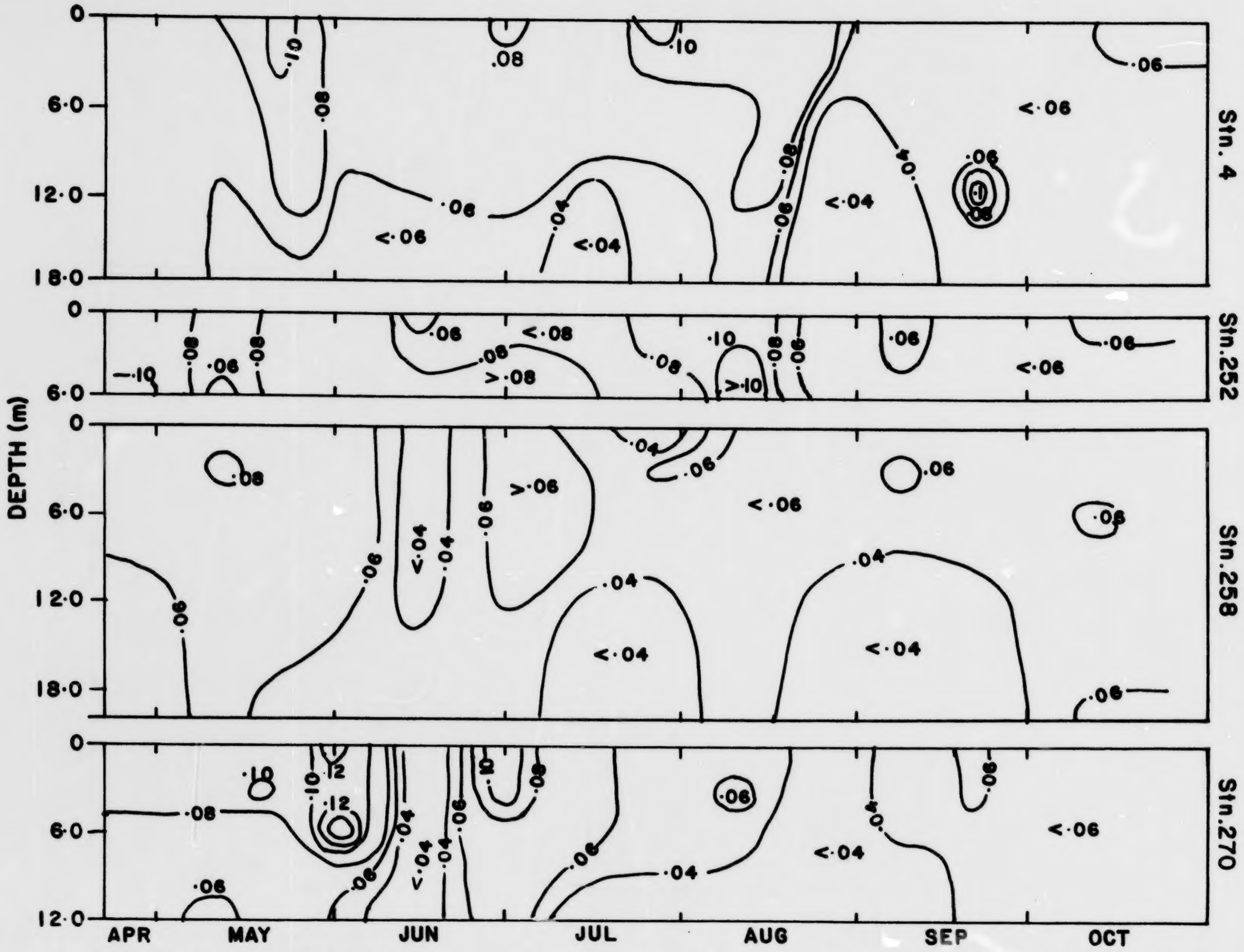

FIGURE 18: ISOPLETHS OF TOTAL PHOSPHORUS (mg/l as P), HAMILTON HARBOUR, 1977.

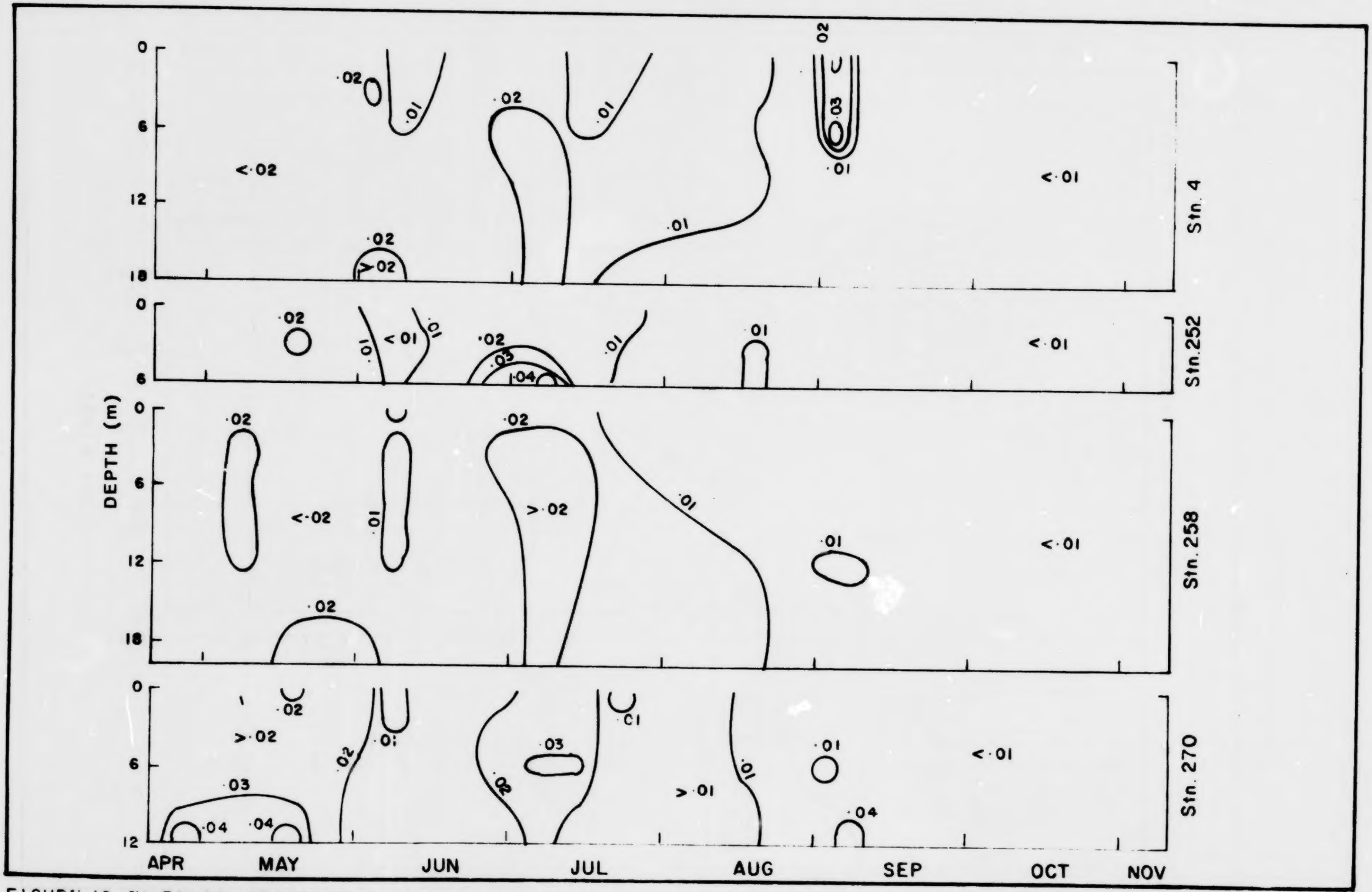

FIGURE 19 FILTERED REACTIVE PHOSPHORUS ISOPLETHS, AT MAJOR SAMPLING STATIONS, HAMILTON HABOUR 1976

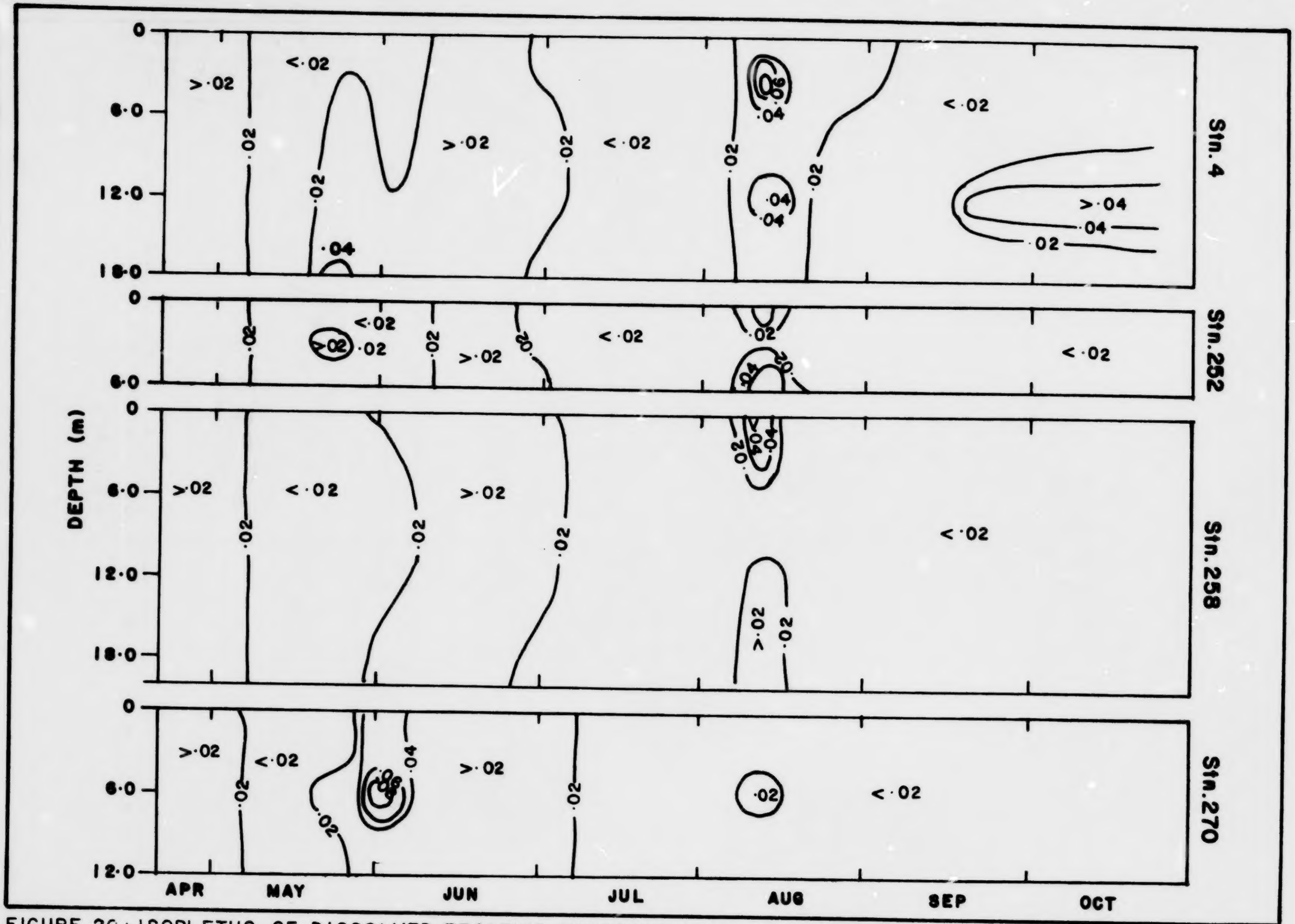

FIGURE 20: ISOPLETHS OF DISSOLVED REACTIVE PHOSPHORUS (mg/ℓ as P), HAMILTON HARBOUR, 1977

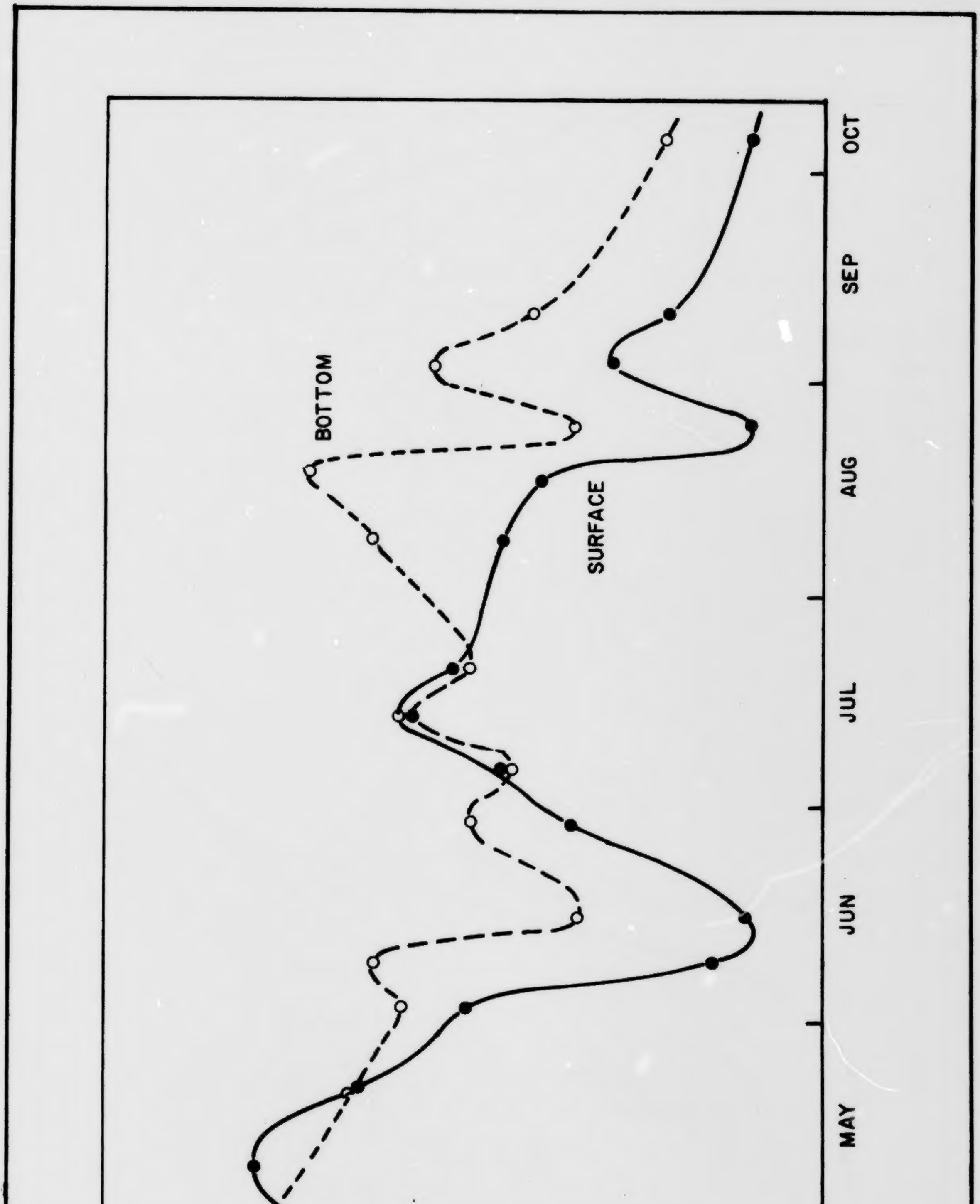

FIGURE 21 : VARIATION OF SILICA WITH SAMPLING DATE, 1976 SURFACE AND BOTTOM MEANS

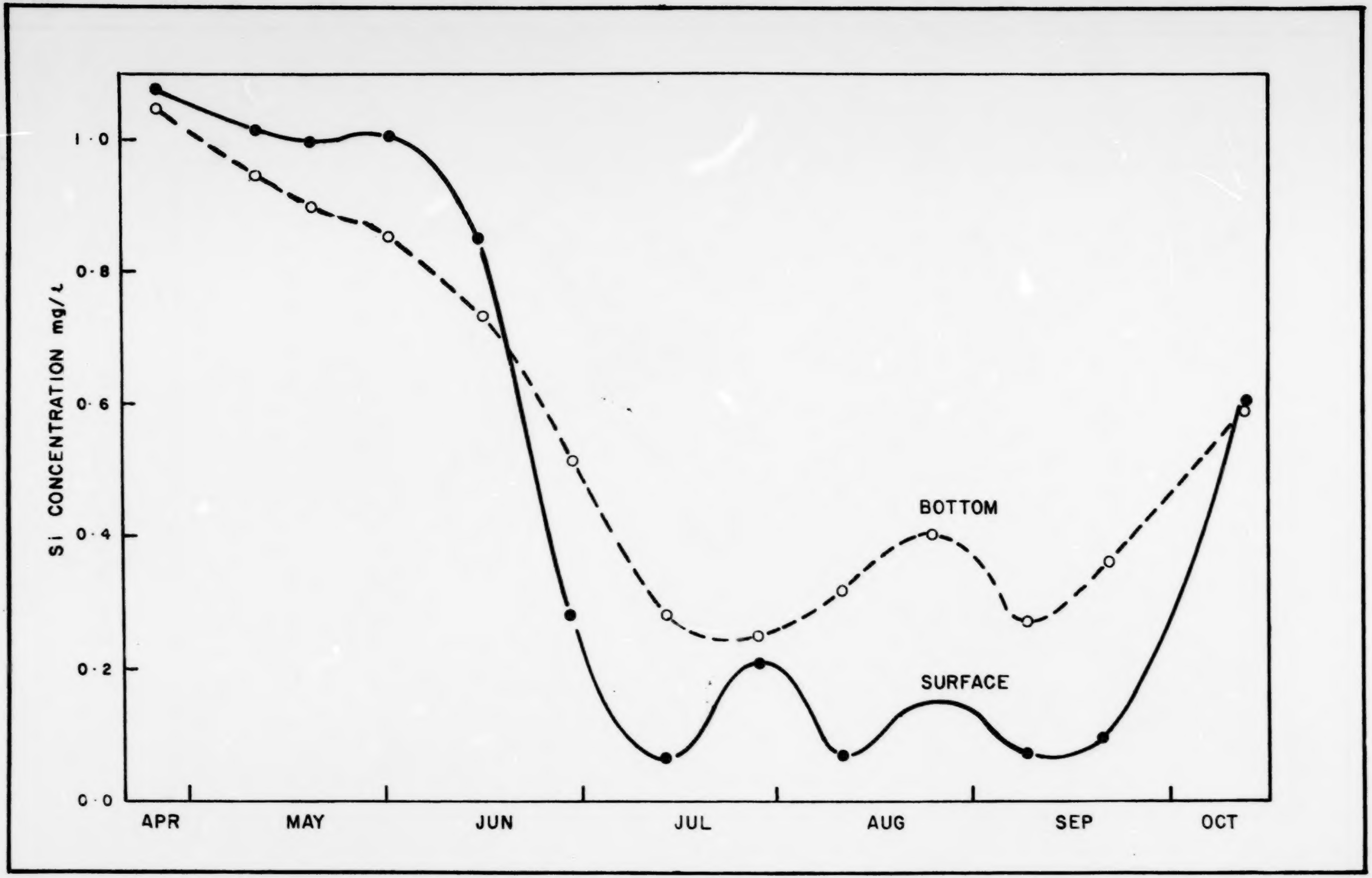

FIGURE 22: VARIATION OF SILICA WITH SAMPLING DATE, 1977 SURFACE AND BOTTOM MEANS.

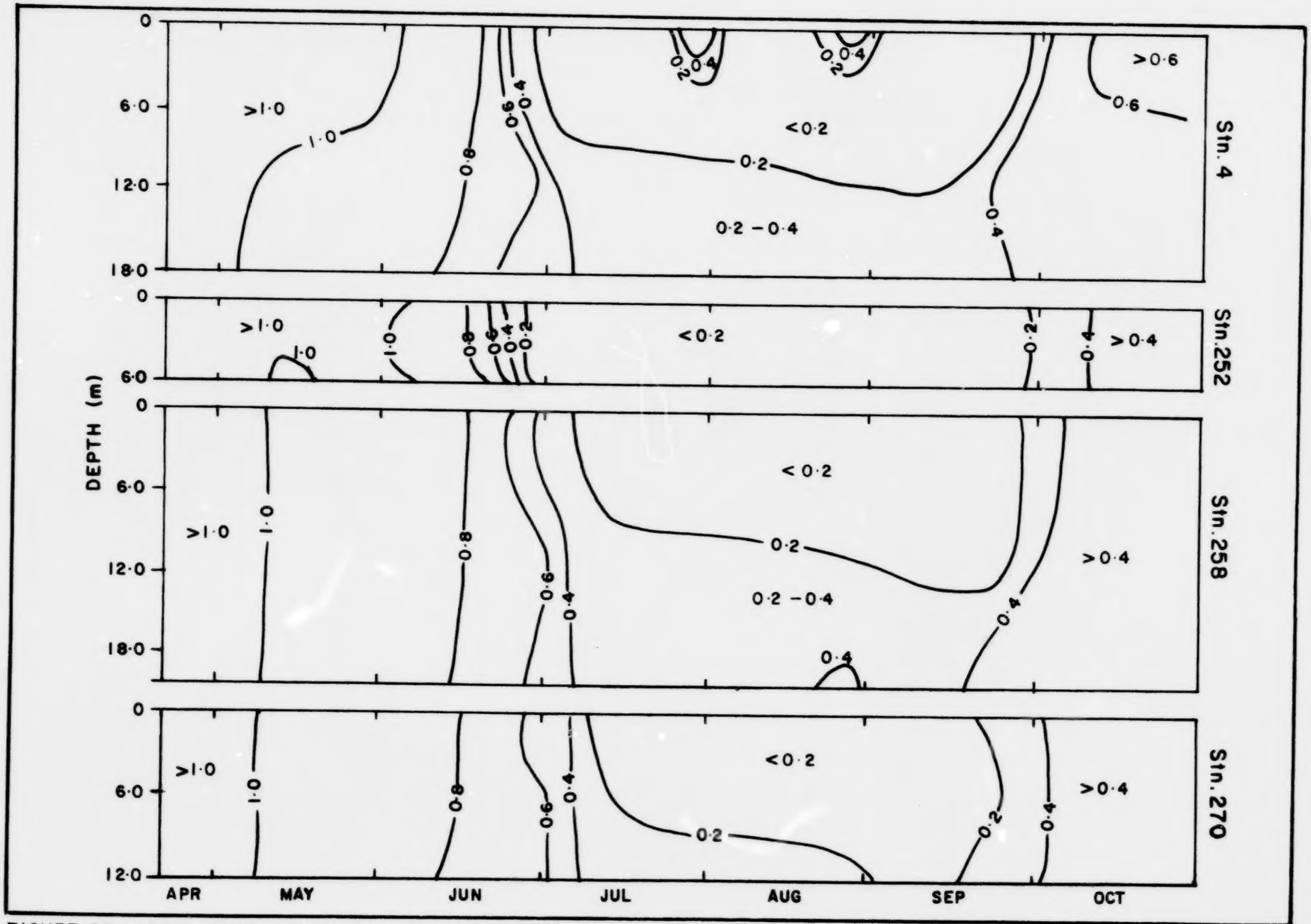

FIGURE 23: ISOPLETHS OF DISSOLVED REACTIVE SILICA (mg/ℓ as Si), HAMILTON HARBOUR, 1977

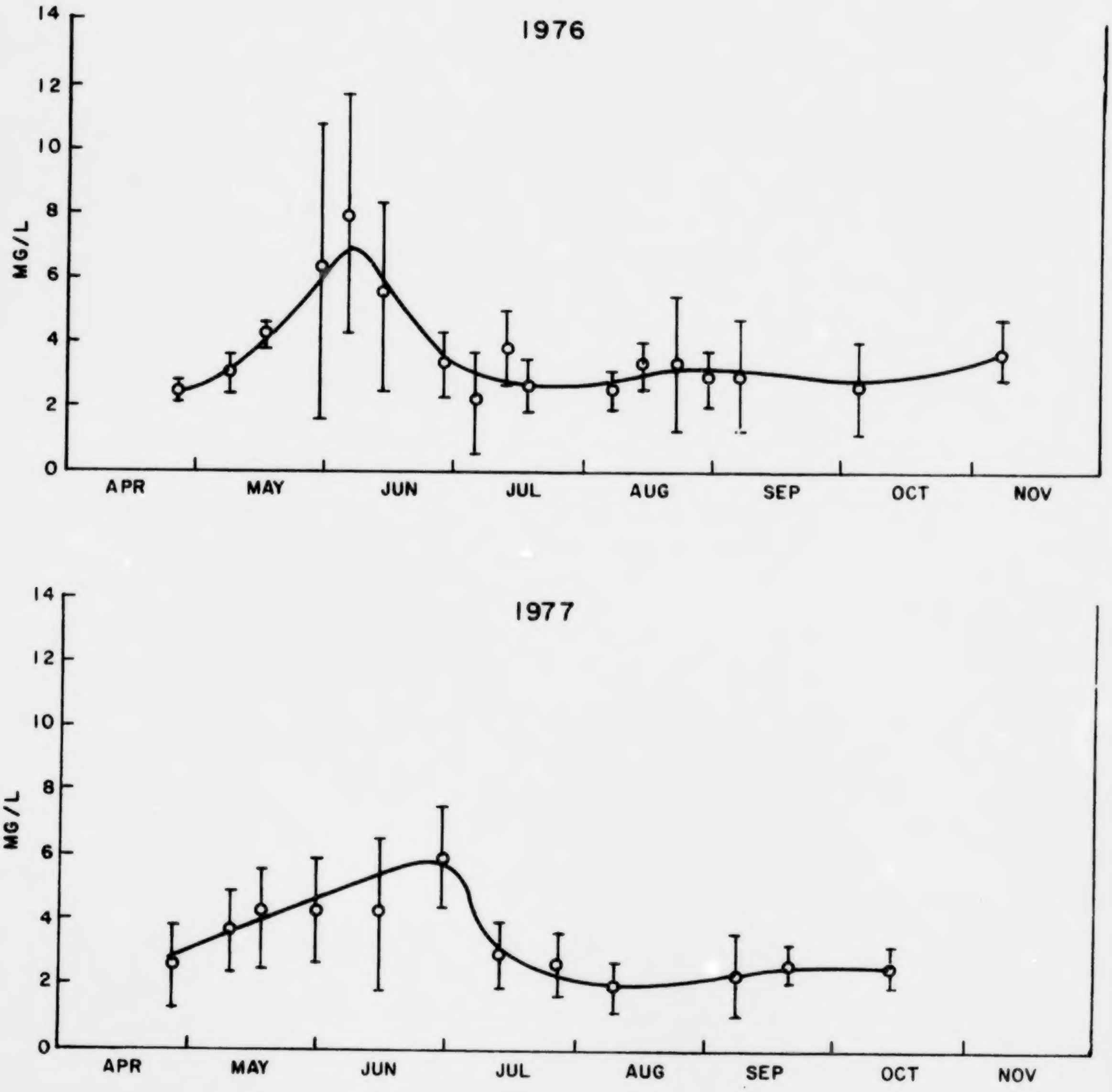

FIGURE 24: HARBOUR - WIDE MEANS OF BIOCHEMICAL OXYGEN DEMAND, HAMILTON HARBOUR, 1976 — 1977

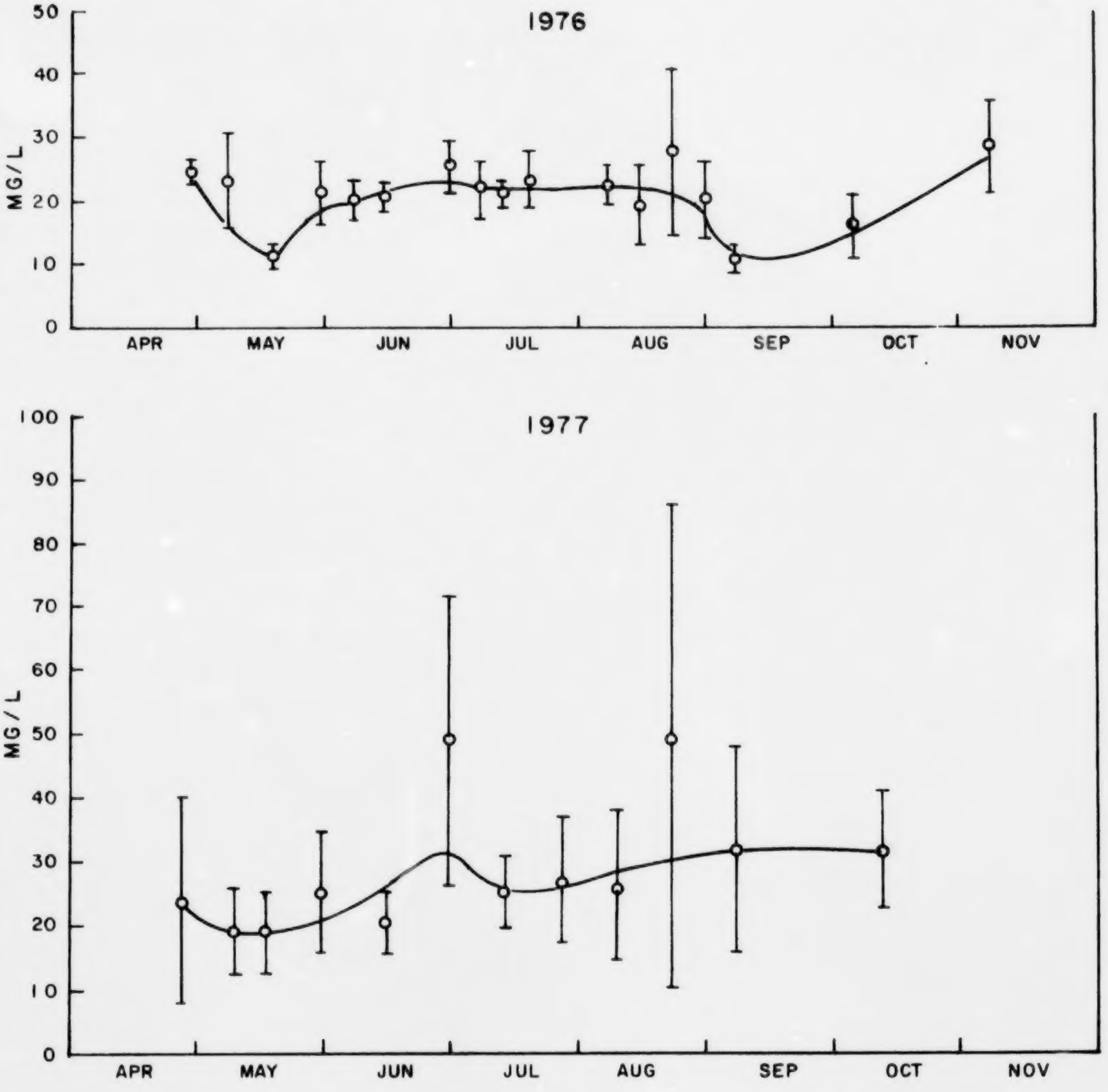

FIGURE 25 : HARBOUR -- WIDE MEANS OF CHEMICAL OXYGEN DEMAND, HAMILTON HARBOUR, 1976 - 1977

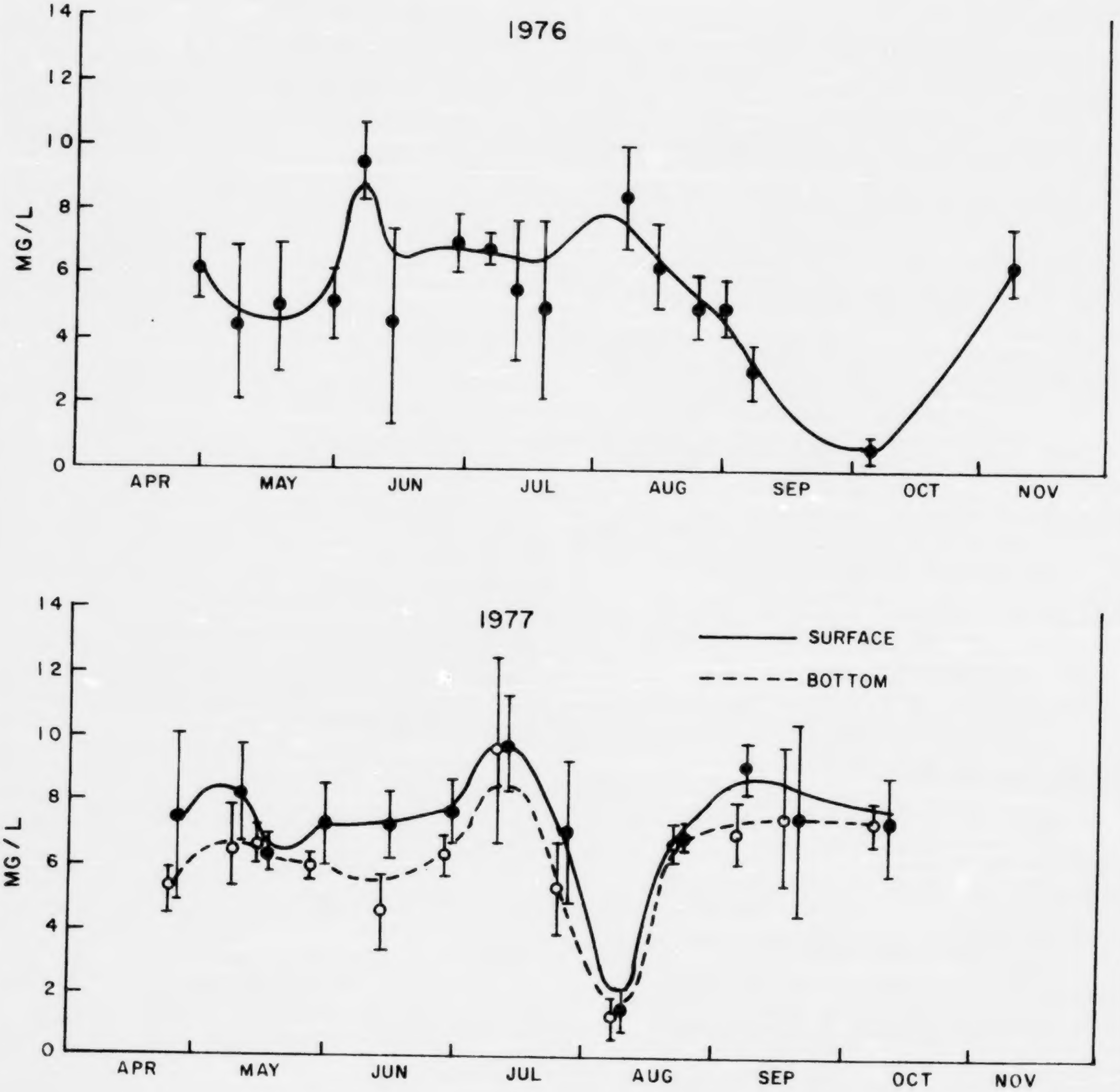

FIGURE 26 : HARBOUR-WIDE MEANS OF TOTAL ORGANIC CARBON, HAMILTON HARBOUR, 1976-1977

Hamilton Harbour Study
1977

VOLUME I

SECTION D

SEDIMENT CHEMISTRY

SUMMARY

The comprehensive sediment surveys conducted in 1975 and 1976 (MOE, 1977, 1978a) indicated heavy enrichment of pollutants throughout most of Hamilton Harbour. Analyses of core samples indicated that surficial sediments were enriched by factors of 4 to 140 compared to sediments 50 or more centimeters below the sediment-water interface. The harbour sediments were found to be most severely polluted with respect to zinc, lead and chromium, and to a lesser extent, cadmium and mercury. The highest pollutant concentrations were found in deep water and adjacent to the outfalls. Enrichment next to the outfalls was observed to be a function of the pollutants discharged; these samples were classified into separate groupings as a result of factor analysis.

INTRODUCTION

In May and October 1977, single samples were taken by Ekman dredge from 25 locations in Hamilton Harbour. In addition, dredge samples were collected at the four major sampling stations (4, 252, 258 and 270) monthly during the summer. The locations sampled are shown in Figure 1. The primary purpose of these surveys was the study of bottom fauna (Section J). Samples collected in May were analyzed for loss on ignition, free ammonia, total Kjeldahl nitrogen, total phosphorus, arsenic, iron, lead, zinc, ether extractables, mercury and percent water. In addition to most of the above parameters, October samples were analyzed for copper, nickel, cadmium, chromium, BOD and COD. Most of these parameters were also determined on the monthly summer samples. The results of these analyses are presented in this section and compared to the results from the 1976 core samples.

RESULTS

Means and standard deviations of all results obtained in May and October are given in Table 1. No significant differences were found between the two sets of samples except for NH_3, which was higher in October and ether extractables, which was higher in May.

The increase in ammonia-N could indicate some bacterial mineralization of organic N during the summer months. A qualitatively similar increase in sediment and interstitial water ammonia-N was found during anaerobic incubation of Wisconsin Lake sediments (Graetz, Keeney and Aspiras, 1973); unlike Hamilton Harbour, ammonia was released to the water column during their experiments. As reviewed by Keeney (1973), the interstitial water plays a vital role in sediment-water nitrogen relations; microbial reactions and redox relationships are all important in determining the seasonal nitrogen dependence. Therefore, a proper explanation of the observed increase in sediment ammonia concentrations cannot be offered without a detailed study of the pore water and exchange reactions. The sediment NH_3-N comprises only 1 to 5% of the TKN. That the sediment N is mainly organic in nature is not surprising for a water body such as Hamilton Harbour, which receives large amounts of organic waste inputs (Volume II).

Results of the monthly sediment samples (Table 1a) taken at the four major sampling stations indicated no significant changes from one month to the next, except for total phosphorus at locations 4 and 258 in July, when values of 0.7 mg/g were obtained, in contrast to values of 4 to 5 mg/g obtained on other dates for these locations. This result does not relate to aerator operation or any changes in water chemistry (Section C, Water Chemistry), and cannot be explained. In addition, low values were obtained for all parameters at station 4 in May; results for samples taken during the summer at this location (except for July total P mentioned above) are similar to October results, implying that the May samples may not have been collected at quite the same location.

HEAVY METALS

Results for heavy metals in the 1977 dredge samples are similar to, or slightly higher than, those for the top portions of core samples obtained during 1976 (MOE, 1978a). Except for mercury, these results are also almost identical to those obtained for the dredge samples taken in May 1975 (MOE, 1977).

As was done with the 1975 and 1976 data (MOE, 1977, 1978a), the concentrations of the 1977 sediment dredge samples were compared to values characteristic of "elevated" and "excessive" heavy metal concentrations of Great Lakes sediments (Fitchko and Hutchinson, 1975). These authors considered "elevated" sediment heavy metal concentrations to be those of more than the mean + two standard deviations of the concentrations from uncontamined Great Lakes river mouth areas, and concentrations more than 5 times these values to indicate "excessive" values. Figures 2-8 indicate the areas of elevated concentrations for Hg, Pb, Zn, Cr, Ni, Cu and Cd for 1977. Averages of May and October data were used where available (Hg and Pb), otherwise data represent a single survey. Monthly data were not included as these represent only four sampling locations. A figure for cobalt was not presented as this metal indicated elevated concentrations only at the Ottawa Street slip (station 2) and was below the "elevated" limit elsewhere.

Mercury, zinc, lead and chromium show "excessive" concentrations for the entire harbour, except for the shallowest areas and the zone immediately adjacent to the ship canal. Copper presents "excessive" concentrations in most of the deep zone and in the southeastern portion of the harbour. Cadmium has "excessive" concentrations in most of the deep zone. These metals are "elevated" in most of the remainder of the harbour. Nickel presents "excessive" concentrations only in the Ottawa Street slip and is "elevated" in most other areas except the northern portion of the harbour. Comparison of these results to 1976 data is facilitated by considering the station number and recorded water depths at the north shore locations during the October 1977 cruise: 253, 4m; 257, 10m; 260, 12.5 m; and 263, 14.0 m. This shows that only station 253 can be considered as representative of the "shallow" pairs of north shore stations used in 1976 (MOE, 1978a) and indicates that the excessive concentrations obtained along the north shore for several parameters are not significantly different from 1976 results. When water depths at the various stations are considered, no significant differences between 1976 and 1977 samples exist, except for mercury. In the case of mercury, the 1977 dredge samples (Figure 2) present a far larger zone of excessive concentrations than the samples for 1976. Excessive concentrations occur along the industrial shoreline and in almost the entire deep portion of the harbour, except for an area in the eastern part of the harbour which was influenced by harbour-lake exchange. Concentrations of mercury in the shallow northern and western areas were below the "elevated" limit to "elevated" in 1977; this was similar to 1976 considering the distribution of sampling locations used in the two years. If the dredge sampler took a shallower cut than the 5 to 7 cm depth used for core sectioning in 1976, and the heaviest mercury contamination is located within the topmost few centimetres, this could explain why the 1977 concentrations are higher than those of 1976.

The high mercury concentrations observed in the deep water sediments are considerably less than those adjacent to the St. Clair River chlor-alkali industries, and comparable to downstream areas (Lakes St. Clair and Erie) affected by these industries. Values in central Lake St. Clair have ranged from 0.7 to 3 ug/g in the period 1973-76 (MOE, unpublished data), and 1.0 ± 0.5 ug/g in western Lake Erie for 1976 (MOE, 1978b). The highest mercury concentration in Hamilton Harbour sediments in May 1977, 2.7 ug/g, occurred at station 262 (Randles Reef) and appears to indicate that discharge of this metal is in that vicinity. This value is similar to the highest recent values observed in Lake St. Clair and the western basin of Lake Erie (MOE, 1978b; Walters, Wolery and Myser, 1974). The October value at the same location was only 0.93 ug/g; this difference presumably indicates a large spatial variability rather than an actual decline. These values are higher than those for most other Great Lakes areas, and indicate a need for further investigation.

RESULTS OF FACTOR ANALYSIS

The results from the May and October 1977 dredge samples were processed by Q-mode factor analysis of the similarity coefficients obtained from comparison of the ratios of pollutant concentrations between the various samples obtained at one time, as was done with previous years' data (MOE, 1977, 1978a). Q-mode factor analysis divides samples into different groups with samples of similar characteristics being grouped together. The results are shown in Figure 9 for May and Figure 10 for October.

Although minor differences were present between the two series of samples, the factor patterns produced were similar to those observed in previous years. Both series of samples produced a principal factor relating all deep water areas. The stations affected most by waste discharges (268, Hamilton STP; 2, Ottawa Street slip; and 262, Randles Reef) each produced a unique factor, as did station 264, which is influenced by Cootes Paradise. Station 267 presented a unique factor in the May series only. Relationships observed in 1977 along the north shore are less complex than those observed in 1976, and relate at least partially to water depth at the sampling locations. In May, station 252, the shallowest location sampled, presented a unique factor, while the remaining north shore points were related to the principal factor. In October, one factor (factor 2) related stations 252, 253 and 257, while another factor (factor 8) related points 260, 263, 15, 270 and 265 in the west end of the harbour. Relationships in this part of the harbour were less distinct, however. Locations 15 and 270 were also related to the principal factor; locations 263 and 265 were related to factor 2 if the analysis was stopped at 7 factors. Factors 2 and 8 are similar to factors observed in 1976 at shallow and intermediate water depths along the north shore and west end of the harbour. Factor 2 represents the shallowest locations while factor 8 represents locations of intermediate depth including the far west end of the industrial shoreline as observed in 1976. Factor 8 is sensitive to the chemical parameters used in the analysis, and does not appear when only the common parameters analyzed for in both months are included. Thus its presence appears to be related to the additional parameters determined in October.

In both months, the effect of lake-harbour exchange is again observed at stations 269 and 1030. An important difference, however, is the inclusion of station 4 in this factor in May only. The latter was completely unexpected, considering the deep water nature of this location, and the fact that the sample taken slightly to the east (at station 251, closer to the beach strip) was included in the principal factor. Pollutant concentrations for the May sample at station 4 were much lower than those for samples taken from other deep water areas; these were confirmed by repeat analyses for several parameters. This result (like the depth profiles in the 1976 core taken at Station 4) suggests that some transport of sand through the Burlington Ship Canal, and southward, is occurring. Possibly the May sample was taken from a slightly different location; samples taken monthly during the summer at station 4 were apparently very similar to the October sample. The effect of Lake Ontario is not felt much farther west, as shown by the inclusion of station 22 (not sampled in previous years) with the principal factor.

It is possible that station 4, and the area immediately to the west (station 255) represents a zone of fluctuating transport processes. As in 1975 and 1976, no one single factor represented station 255 in May; however in October, this station was represented by the principal factor.

As the zones close to the outfalls presented unique factors similar to those observed in previous years, they were again used to indicate areas which are most affected by waste discharges (Table 2). The zones with highest pollutant concentrations are Randles Reef (Pb, Hg, Zn, Fe, Ether Extractables) and the Ottawa Street Slip (Pb, Ni, Cr, Fe, As, Cu, Ether Extractables). The Hamilton sewage treatment plant vicinity appeared to be less severely contaminated relative to other outfall locations in 1977. A possible source of cadmium in the southwestern part of the harbour may be indicated by the relatively high value at station 270. This fact, which was also observed in 1976, is worth further investigation.

Interparameter relationships in 1977 were also similar to previous years, as indicated by R-mode factor analysis for May (Table 3) and October (Table 4). R-mode factor analysis divides chemical parameters into groups with similar characteristics like geochemical behaviour or discharge patterns. Transition metals (Fe, Cu, Ni and Co) were associated in one factor and post-transition metals (Zn, Pb, Cd and Hg) were associated in a second factor. Nutrients (N and P) were related in a third factor in May, but were related to post-transition metals in October. The fact that both these relationships involving N and P have previously been observed does indicate year-to-year consistency. Consistency is also seen in the various measures of organic matter: COD (October) was related to transition metals as observed in 1975 and 1976, but LOI (both sets) was related to post-transition metals, as observed in 1975. In both months, ether extractables presented a separate factor which was somewhat related to Hg, and BOD (October) presented another separate factor. It is obvious that different organic components of the sediment react differently; a study of the chemical makeup of the organic compounds in the sediments would be interesting though probably difficult in practice. Somewhat surprisingly, ammonia was related most strongly to ether extractables in October. In May, ammonia was not included in the factor analysis as it was not determined on many of the samples.

GRAIN SIZE ANALYSIS

An initial attempt at grain size analysis, by sieve and hydrometer, was performed on samples taken from stations 4, 252, 258 and 270 in September. The results are given in Table 5. The sample at station 252 appeared to consist mainly of fine sand with some coarser fractions; unfortunately, the analyses are not consistent, with the total (sand and clay) percentage being greater than 100%. The results of the deeper locations are similar to each other, as might be expected considering other evidence. Considering the fact that the finest sediments generally tend to settle to the deepest points, the lower proportion of clay and higher proportion of silt at station 258 is somewhat surprising.

Grain size analysis is important as heavy metal content increases significantly as particle size decreases (Forstner, 1976). If future grain size analysis is performed, chemical analysis should be done on various fractions to study the relationship between grain size and pollutant content, in particular as it relates to distributions throughout various parts of the harbour.

DISCUSSION

(a) COMPARISON WITH PREVIOUS YEARS

In general, the 1977 Hamilton Harbour sediment chemistry results were similar to those observed in recent years, taking variations in sampling locations and method into account. The October results confirm the 1976 finding (MOE, 1978) that the industrial southern and southeastern areas produce a greater influence on the deep water sediments than do the southwestern part of the harbour and moderate-depth northern areas. Although 1977 sediment mercury concentrations are generally higher than 1976 values, they are still far lower than results obtained for areas in the St. Clair River directly affected by the chlor-alkali industries. The mercury results for Randles Reef (station 262) in May and October indicate a possible high spatial variability as already discussed.

The body of general sediment chemistry data gathered in the period 1975 to 1977 represents a good indication of general harbour sediment quality. It is suggested that general sediment surveys be discontinued for a few years and efforts be directed towards special studies. In particular, the sediment-water interface deserves further study as chemical and biological reactions occurring at this location play a strong role in controlling aqueous heavy metal and nutrient concentrations. Interparameter relationships as depicted by R-mode factor analysis of the various sample series indicate that relationships between nutrients and heavy metals are more complicated than the simple iron-phosphorus-DO system. This topic has been discussed more thoroughly (MOE, 1978a, Section D), and future projects have been suggested for further study of the sediment-water interface. These include partial extraction schemes for nutrients and heavy metals in sediment samples, experimental measurements of nutrient and heavy metal uptake and release, and thorough study of the chemistry of the water from within a few centimeters of the interface with the aid of a special water sampler.

(b) INTERSTITIAL WATER

In addition to the above-mentioned studies, a study of the composition of interstitial water is desirable. This is important because the dynamics of nutrient and heavy metal availability to the water column is more dependent upon the composition of the interstitial water than of the sediments. Interstitial water makes up an average of over 50% of Hamilton Harbour surface sediments (Table 1), with the highest values being found in the deep-water and south shore areas. Interstitial water from reduced sediment cores in western Lake Ontario has been observed to contain 2 to 3 orders of magnitude more dissolved Fe and 3 to 4 orders of magnitude more dissolved Mn compared to lake water (Weiler, 1973). The same author also found around 10 mg/L NH_3 in interstitial water from one of these cores. It should be possible to integrate studies of the interstitial water with the partial extraction studies.

(c) DREDGING

The composition of the interstitial water also plays an important role in the environmental impact of dredging, as carried out for shipping channel maintenance. It is beyond the scope of the present discussion to present a detailed description of the complicated factors which control the uptake and/or release of heavy metals and nutrients during dredging. Patrick, Gambrell and Khalid (1977) have reviewed the factors regulating heavy metal availability during dredging. The most important contributor in these reactions is the pH - Eh relationship. Dissolved ferrous iron in the interstitial waters of the reduced sediment can be rapidly oxidized and precipitated as an amorphous gel, which is capable of adsorbing many heavy metals. Thus the heavy metal concentrations in the water column may remain low provided sufficient dissolved oxygen is present. On the other hand, if heavy metal sulfides are present, oxidation can allow the release of heavy metals to the water column, although these may be adsorbed later on hydrated ferric oxide particles. These mechanisms have been used to explain transient pulses of dissolved mercury observed during simulated dredging experiments (Lindberg and Harriss, 1977).

Organic complexation may mobilize many heavy metals which should otherwise remain insoluble. This is a complicated process which involves both dissolved and insoluble organic materials (Patrick, Gambrell and Khalid, 1977), and is bound to be important in the highly organic Hamilton Harbour environment. If metals are complexed to insoluble high molecular weight organic compounds such as humic acids, these may be released under oxidative degradation of the organic materials; however, this process is very slow, and the released metals would probably be adsorbed by hydrous Fe and Mn oxides. More important is the presence of low molecular weight soluble organic material in the interstitial water or the water column which is capable of complexing significant amounts of otherwise insoluble heavy metals. Despite the fact that Patrick, Gambrell and Khalid (1977) noted that most studies of water quality during dredging operations have shown little or no increase in dissolved metal concentrations, the effect of dissolved organic matter must not be overlooked.

Maintenance dredging of the western portion of the Stelco shoreline (between stations 262 and 259) and near HHC pier 14 (just west of station 262) was performed in 1978. Studies in 1976 (MOE, 1978a) have shown that the central portion of the area does not contain any unusual contaminants; severe pollution occurs only in the region of Randles Reef. Considering the conflicting results concerning the effects of redox potential and organic matter reported above, it is difficult to predict the effect of such dredging on harbour water quality. The most important effect would be the increased DO demand which will be exerted by resuspended material. As the sulfide content of most harbour sediments is low (MOE, 1978a), the metals will not be present as sulfides; therefore, if dissolved oxygen levels are depressed, increased heavy metal concentrations may well be observed, if only temporarily, in the water column.

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TABLE 1

MEAN RESULTS OF HAMILTON HARBOUR SEDIMENT ANALYSES, MAY AND OCTOBER 1977

	May		October	
	Mean	S.D.	Mean	S.D.
LOI (%)	9.1	5.1	9.5	4.7
NH_3 (mg/g)	0.03	0.02	0.10	0.06
TKN (mg/g)	2.9	2.2	2.9	1.5
P (mg/g)	2.7	1.8	2.9	1.7
As	19.	14.	22.	14.
Fe (mg/g)	88.	110.	-	-
Pb	310.	290.	300.	200.
Zn	2600.	2200.	-	-
Ether Ext.	12500.	15000.	7600.	6000.
Hg	0.7	0.6	0.6	0.4
H_2O (%)	57.	18.	58.	18.
Ni	-	-	52.	37.
Cd	-	-	6.3	4.2
Co	-	-	12.	4.
Cu	-	-	110.	90.
Cr	-	-	220.	200.
BOD	-	-	2.6	2.2
COD	-	-	150.	90.

Note: All analyses are in ppm (ug/g), unless otherwise stated.
Samples collected by Ekman dredge.

TABLE 1A

MEAN RESULTS OF MONTHLY HAMILTON HARBOUR
SEDIMENT SAMPLES, JULY-SEPTEMBER 1977

	July	August	September
Loss on Ignition (%)	8.0	9.7	10.3
Total Kjeldahl N (mg/g)	2.4	3.7	3.5
Total P (mg/g)	1.6	3.7	3.7
Cu	120.	130.	120.
Ni	50.	50.	50.
Pb	350.	360.	330.
Zn	2200.	3500.	3600.
Cd	9.3	9.2	9.1
Cr	240.	260.	240.
Mn	2000.	1900.	-
Fe (mg/g)	80.	120.	-
As	24.	23.	24.
Co	13.	12.	11.
Hg	0.7	0.7	0.6

Note: Above results are means of samples taken at stations 4, 252, 258 and 270.
All results are in ug/g, unless otherwise noted.

TABLE 2

SHALLOW ZONES EXHIBITING HIGHEST POLLUTANT CONCENTRATIONS, HAMILTON HARBOUR, 1977

Parameter	May		October	
	Station	Concentration	Station	Concentration
Pb	262	1200	2	860
			262	500
Cd	Not Analyzed		20	8.2
			270	10.
Hg	262	2.7	20	1.3
	20	1.4	262	0.93
	256	1.2		
Ni	Not Analyzed		2	190
Cr	Not Analyzed		2	860
Zn	262	7000	Not Analyzed	
Fe (mg/g)	2	340	Not Analyzed	
	256	170		
	262	117		
Ether Ext. (mg/g)	262	68	256	17.7
	256	40	267	16.2
	268	25	20	14.0
	2	22.6		
As	256	50	2	57
	2	45		
Cu	Not Analyzed		2	380

Note: All results in ug/g unless otherwise stated.

TABLE 3

R-MODE FACTOR ANALYSIS OF MAY 1977
HAMILTON HARBOUR SEDIMENT SAMPLES

Variable	Communality	Factor 1	Factor 2	Factor 3	Factor 4
LOI	.8957	.631	.054	-.575	.405
TKN	.9758	.194	.002	-.936	.248
P	.9556	.379	.098	-.896	-.007
As	.9583	.544	.772	-.256	-.020
Fe	.9731	.006	.955	.061	.241
Pb	.9854	.824	.141	-.296	.446
Zn	.9909	.904	.207	-.319	.168
Ether Ext.	.9728	.395	.257	-.153	.853
Hg	.9787	.751	.122	-.336	.528

TABLE 4

R-MODE FACTOR ANALYSIS OF OCTOBER 1977 HAMILTON HARBOUR SEDIMENT SAMPLES

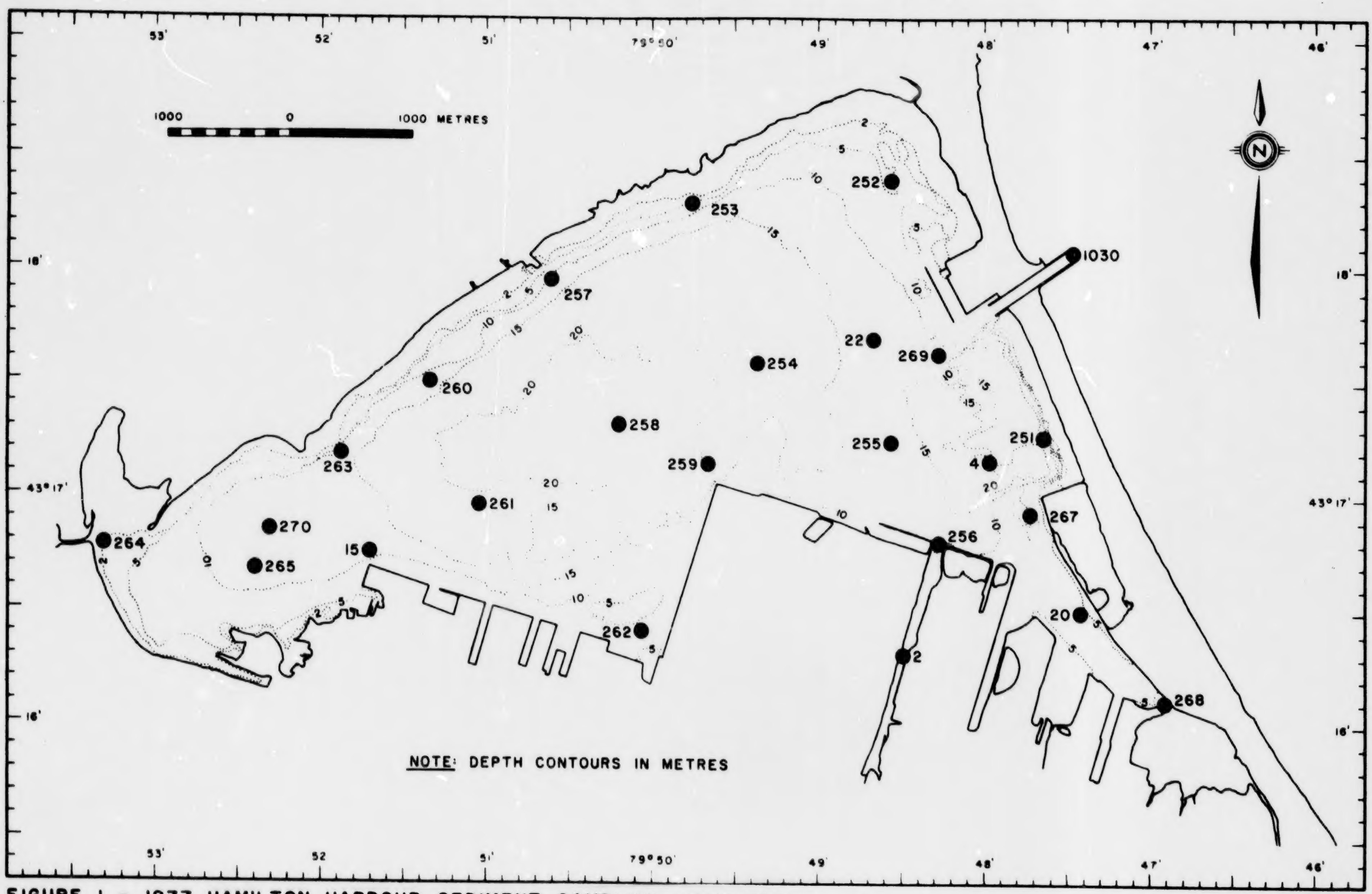
Variable	Communality	Factor 1	Factor 2	Factor 3	Factor 4
Cu	.9656	.902	.245	.295	.069
Ni	.9807	.960	.180	.161	.040
Pb	.9333	.415	.661	.492	.285
Cd	.9187	.153	.860	.273	.286
Cr	.9555	.896	.155	.340	.113
Co	.8941	.815	.463	.072	.103
As	.7935	.766	.240	.268	.277
Hg	.9233	.306	.655	.592	.223
LOI	.8468	.494	.643	.363	.242
BOD	.9567	.178	.388	.209	.855
COD	.9306	.758	.303	.462	.224
NH_3	.8778	.458	.356	.735	.039
TKN	.9542	.285	.840	.344	.220
Total P	.9126	.247	.917	.081	.065
Ether Ext.	.9530	.400	.333	.753	.339

TABLE 5

GRAIN SIZE ANALYSIS
HAMILTON HARBOUR SEDIMENT SAMPLES, SEPTEMBER 1977

Mesh Size	10	18	35	60	120	230	(by difference)	(by hydrometer)
Description	% gravel	% very coarse sand	% coarse sand	% medium sand	% fine sand	% very fine sand	% silt	% clay
Location								
270	0.0	0.1	0.3	0.5	1.5	0.8	29.8	67.0
258	0.0	0.0	0.0	1.0	3.0	2.0	47.0	47.0
4	0.1	0.0	0.7	0.8	5.6	4.3	32.1	57.0
252	7.2	5.6	5.7	5.6	53.8	18.7	(-13)	17.0

Note: Samples were done by wet sieving, with no pretreatment.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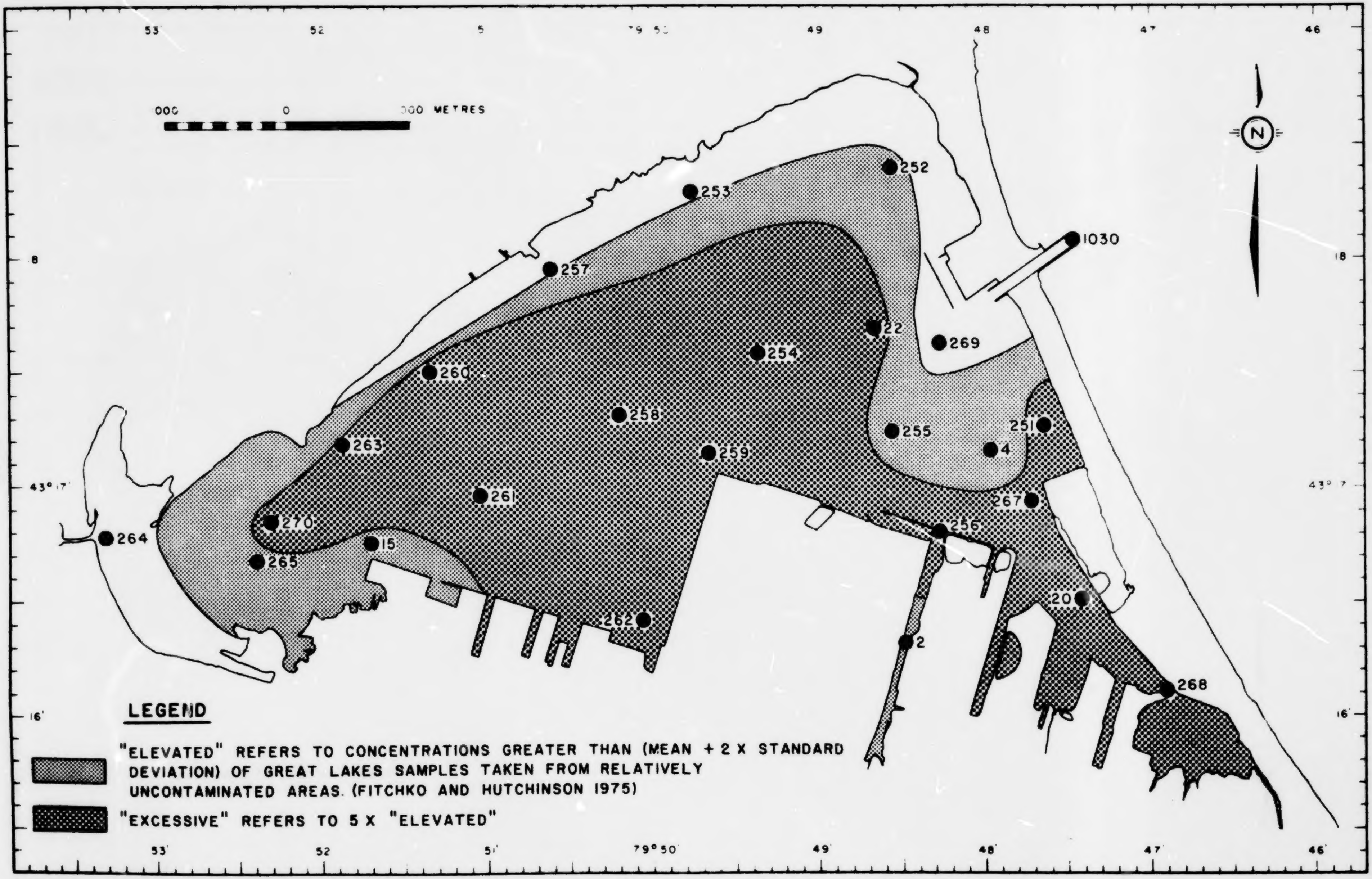
268
NOTE: DEPTH CONTOURS IN METRES

FIGURE 1 - 1977 HAMILTON HARBOUR SEDIMENT SAMPLING LOCATIONS.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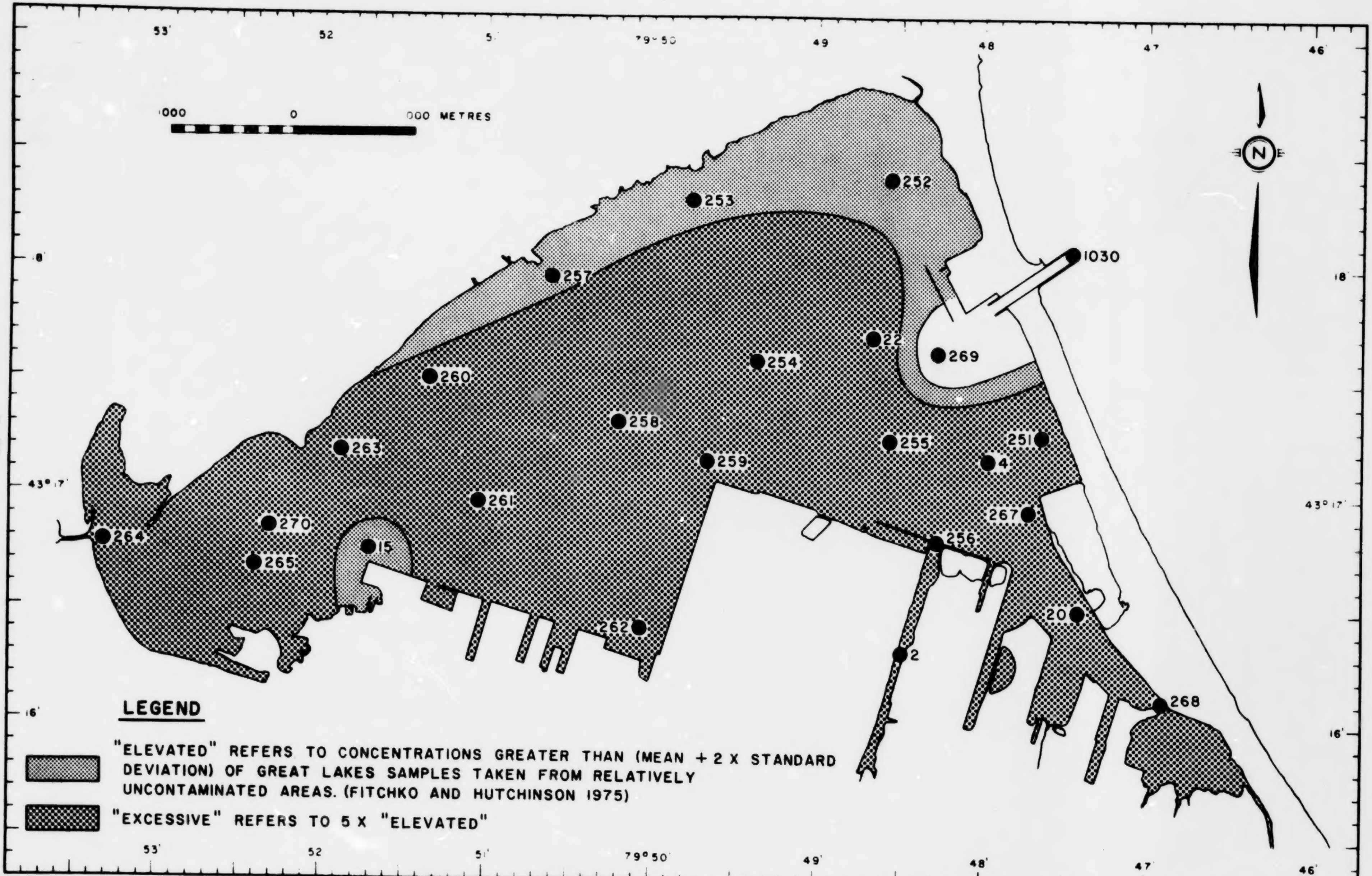
LEGEND
"ELEVATED" REFERS TO CONCENTRATIONS GREATER THAN (MEAN + 2 X STANDARD DEVIATION) OF GREAT LAKES SAMPLES TAKEN FROM RELATIVELY UNCONTAMINATED AREAS. (FITCHKO AND HUTCHINSON 1975)
"EXCESSIVE" REFERS TO 5 X "ELEVATED"

FIGURE 2 - ZONES OF "ELEVATED" AND "EXCESSIVE" CONCENTRATION OF MERCURY TAKEN FROM 1977 (AVERAGE OF MAY AND OCTOBER) HAMILTON HARBOUR SEDIMENT DREDGE SAMPLES.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262
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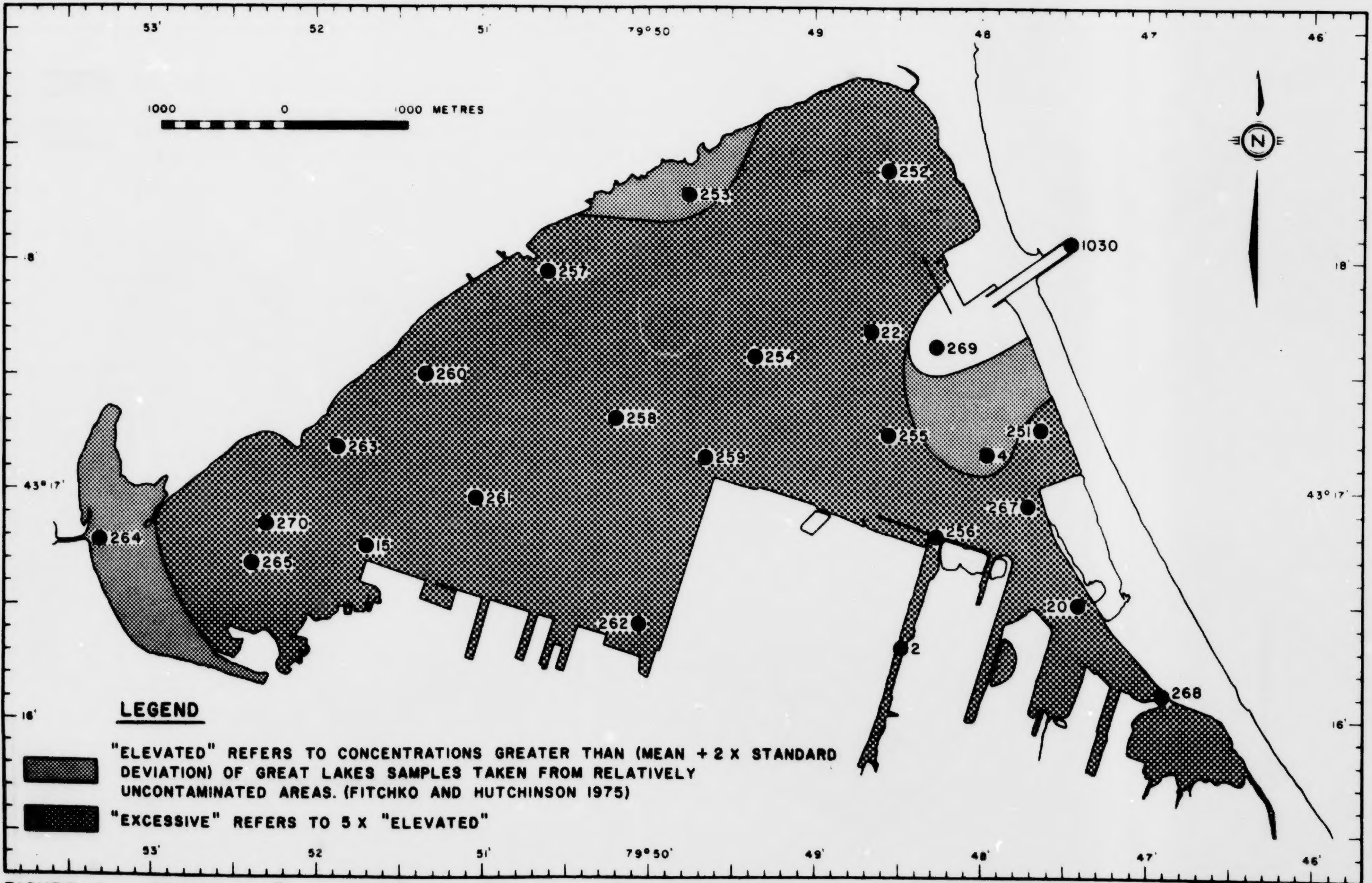
268

LEGEND

▨ "ELEVATED" REFERS TO CONCENTRATIONS GREATER THAN (MEAN + 2 X STANDARD DEVIATION) OF GREAT LAKES SAMPLES TAKEN FROM RELATIVELY UNCONTAMINATED AREAS. (FITCHKO AND HUTCHINSON 1975)

▨ "EXCESSIVE" REFERS TO 5 X "ELEVATED"

FIGURE 3 - ZONES OF "ELEVATED" AND "EXCESSIVE" CONCENTRATION OF LEAD TAKEN FROM 1977 (AVERAGE OF MAY AND OCTOBER) HAMILTON HARBOUR SEDIMENT DREDGE SAMPLES.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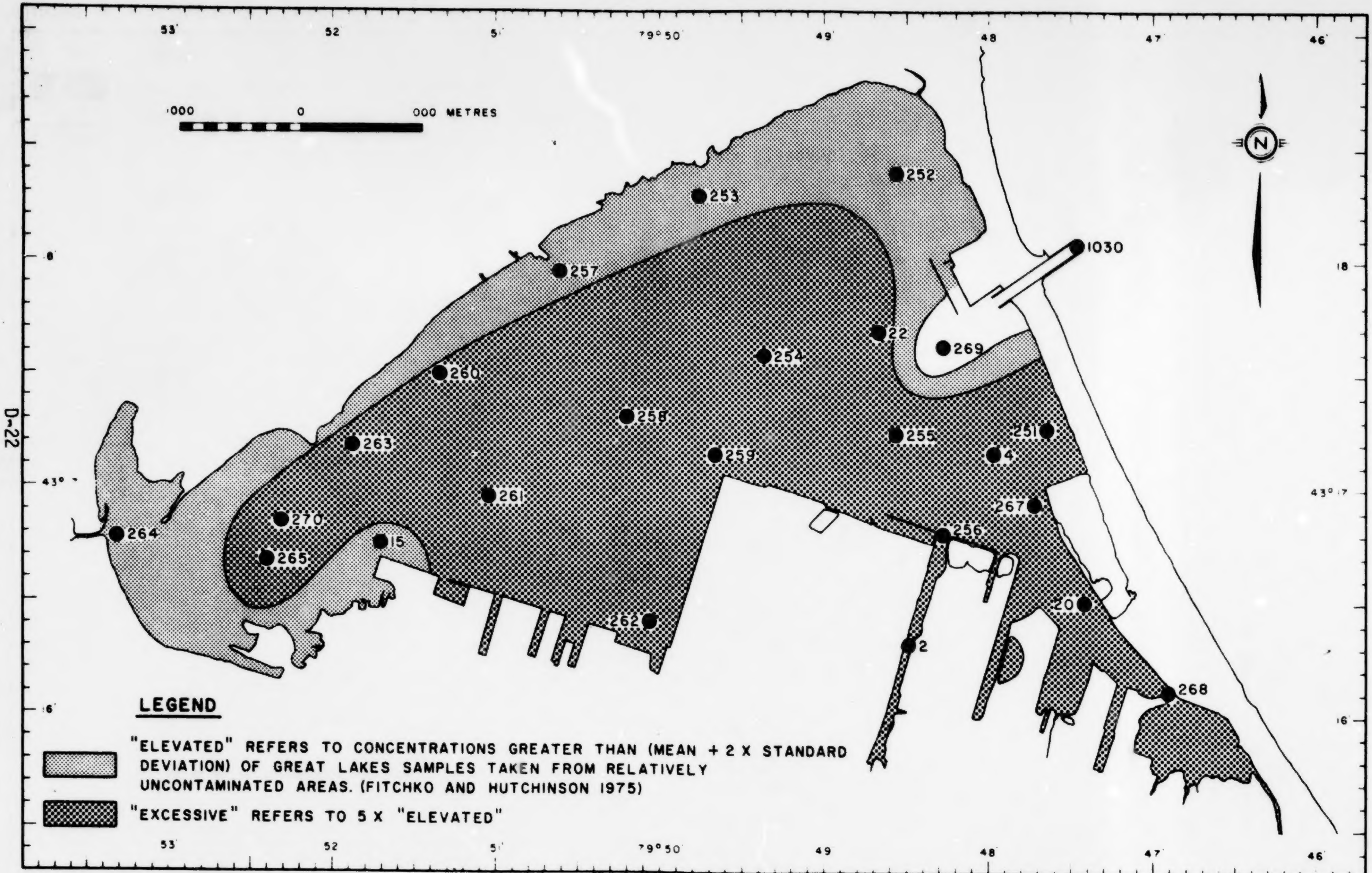
LEGEND
"ELEVATED" REFERS TO CONCENTRATIONS GREATER THAN (MEAN + 2 X STANDARD DEVIATION) OF GREAT LAKES SAMPLES TAKEN FROM RELATIVELY UNCONTAMINATED AREAS. (FITCHKO AND HUTCHINSON 1975)
"EXCESSIVE" REFERS TO 5 X "ELEVATED"

FIGURE 4 - ZONES OF "ELEVATED" AND "EXCESSIVE" CONCENTRATION OF ZINC TAKEN FROM MAY 1977 HAMILTON HARBOUR SEDIMENT DREDGE SAMPLES.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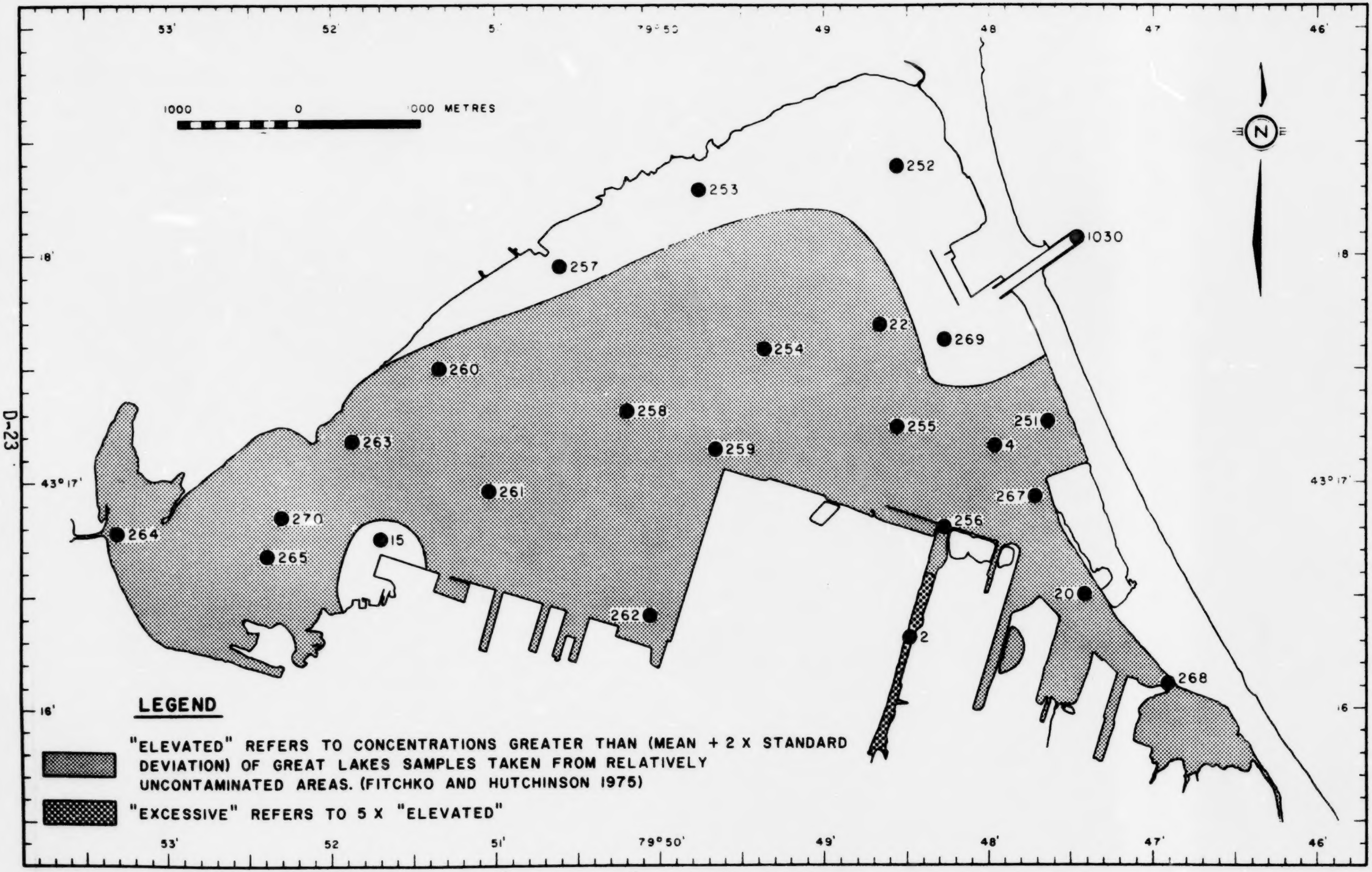
LEGEND
"ELEVATED" REFERS TO CONCENTRATIONS GREATER THAN (MEAN + 2 X STANDARD DEVIATION) OF GREAT LAKES SAMPLES TAKEN FROM RELATIVELY UNCONTAMINATED AREAS. (FITCHKO AND HUTCHINSON 1975)
"EXCESSIVE" REFERS TO 5 X "ELEVATED"

FIGURE 5 - ZONES OF "ELEVATED" AND "EXCESSIVE" CONCENTRATION OF CHROMIUM TAKEN FROM OCTOBER 1977 HAMILTON HARBOUR SEDIMENT DREDGE SAMPLES.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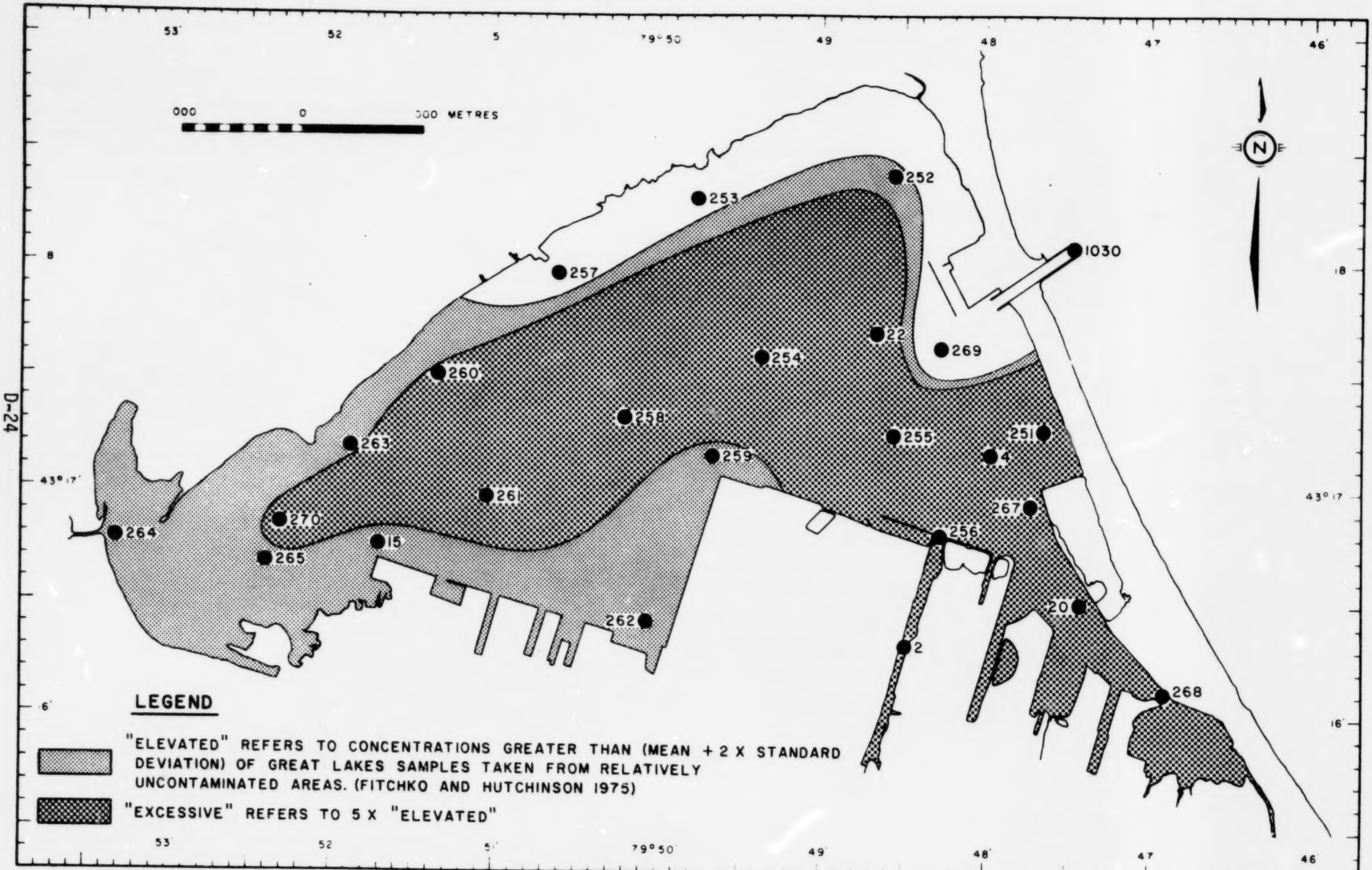
LEGEND
"ELEVATED" REFERS TO CONCENTRATIONS GREATER THAN (MEAN + 2 X STANDARD DEVIATION) OF GREAT LAKES SAMPLES TAKEN FROM RELATIVELY UNCONTAMINATED AREAS. (FITCHKO AND HUTCHINSON 1975)
"EXCESSIVE" REFERS TO 5 X "ELEVATED"

FIGURE 6 - ZONES OF "ELEVATED" AND "EXCESSIVE" CONCENTRATION OF NICKEL TAKEN FROM OCTOBER 1977 HAMILTON HARBOUR SEDIMENT DREDGE SAMPLES.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LEGEND
"ELEVATED" REFERS TO CONCENTRATIONS GREATER THAN (MEAN + 2 X STANDARD DEVIATION) OF GREAT LAKES SAMPLES TAKEN FROM RELATIVELY UNCONTAMINATED AREAS. (FITCHKO AND HUTCHINSON 1975)
"EXCESSIVE" REFERS TO 5 X "ELEVATED"
53'
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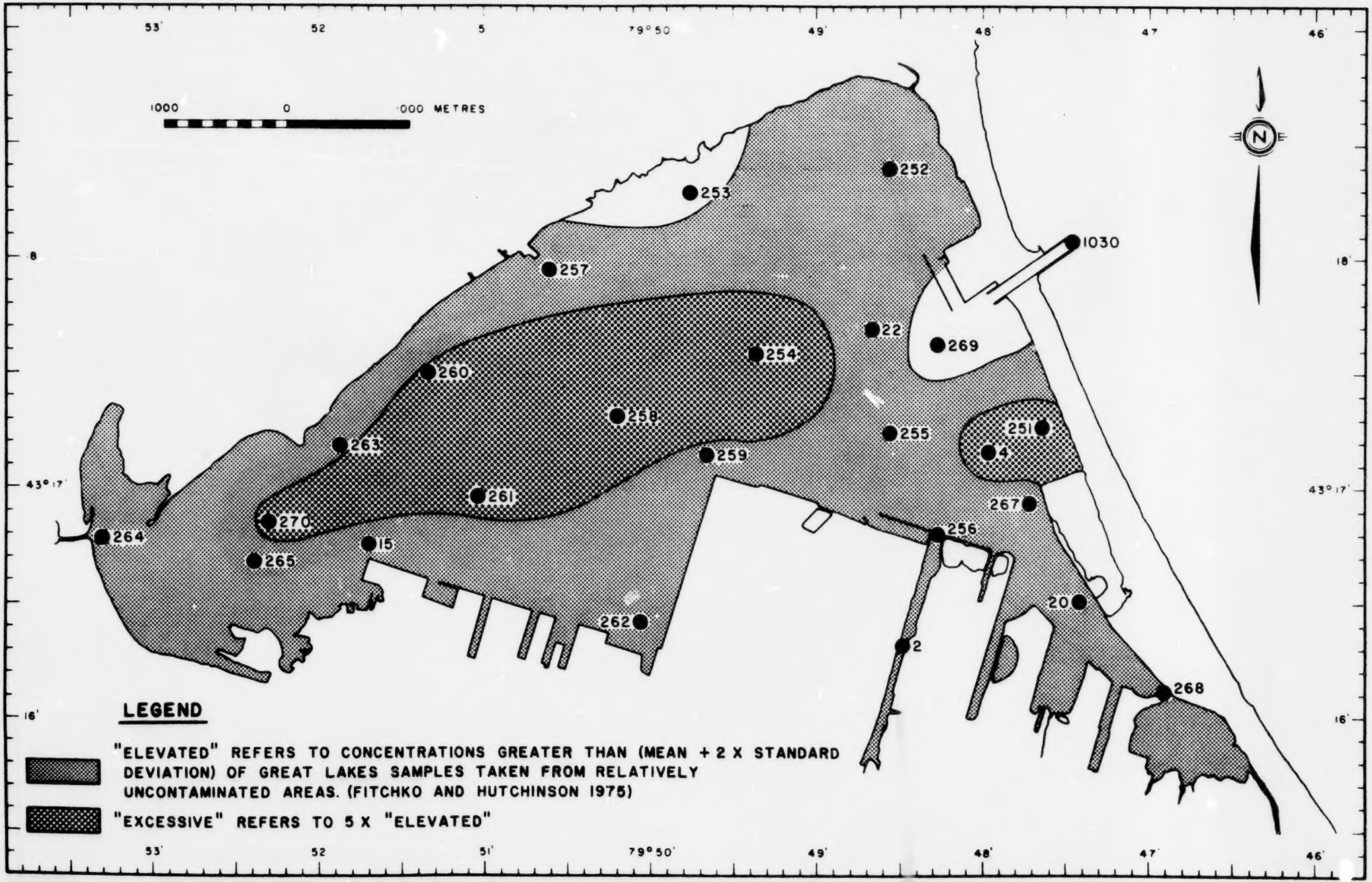
5'
79°50
49'
48'
47
46'

FIGURE 7 - ZONES OF "ELEVATED" AND "EXCESSIVE" CONCENTRATIONS OF COPPER TAKEN FROM OCTOBER 1977 HAMILTON HARBOUR SEDIMENT DREDGE SAMPLES.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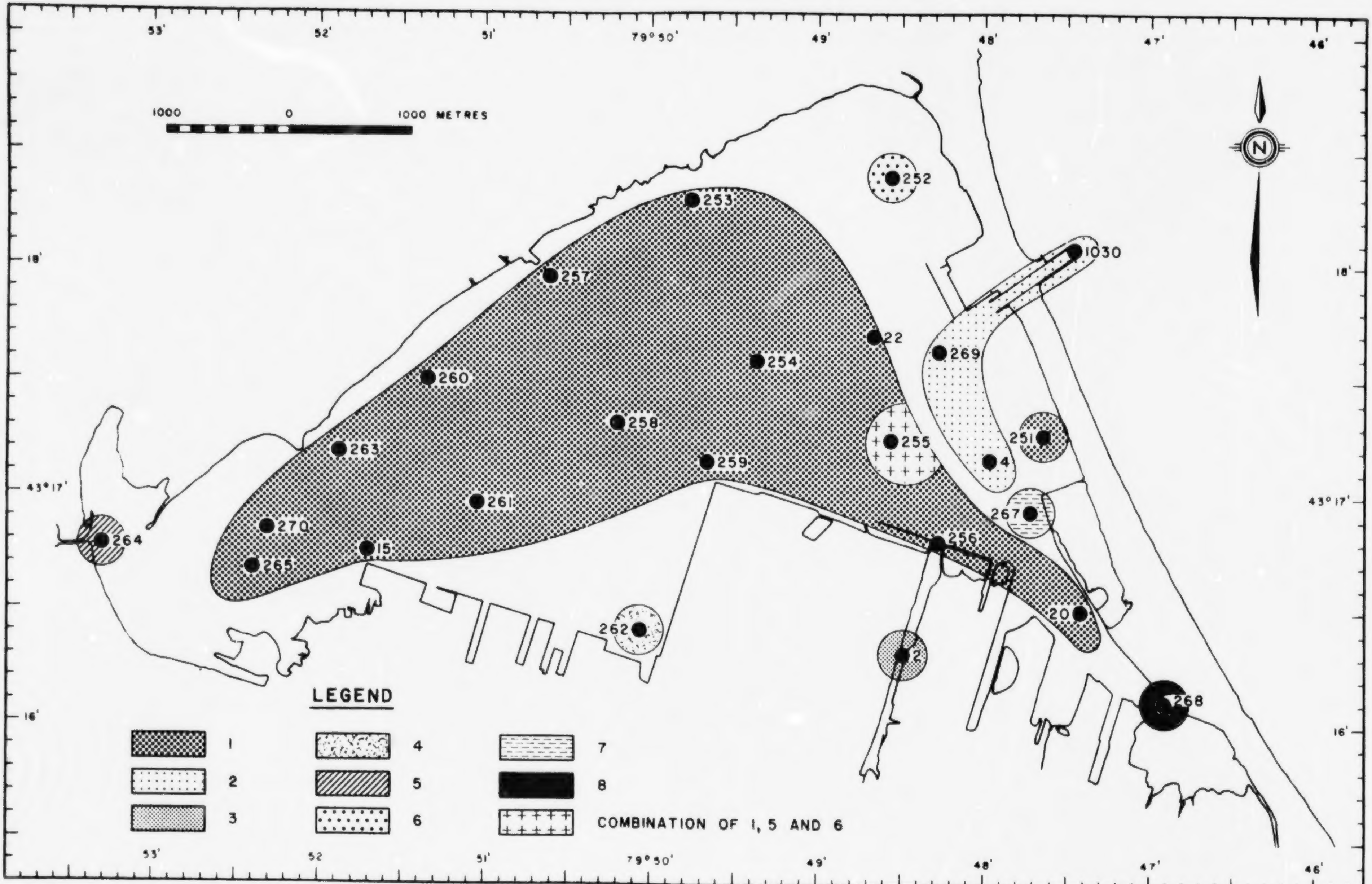
LEGEND

▨ "ELEVATED" REFERS TO CONCENTRATIONS GREATER THAN (MEAN + 2 X STANDARD DEVIATION) OF GREAT LAKES SAMPLES TAKEN FROM RELATIVELY UNCONTAMINATED AREAS. (FITCHKO AND HUTCHINSON 1975)

▩ "EXCESSIVE" REFERS TO 5 X "ELEVATED"

FIGURE 8 - ZONES OF "ELEVATED" AND "EXCESSIVE" CONCENTRATIONS OF CADMIUM TAKEN FROM OCTOBER 1977 HAMILTON HARBOUR SEDIMENT DREDGE SAMPLES.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268
LEGEND
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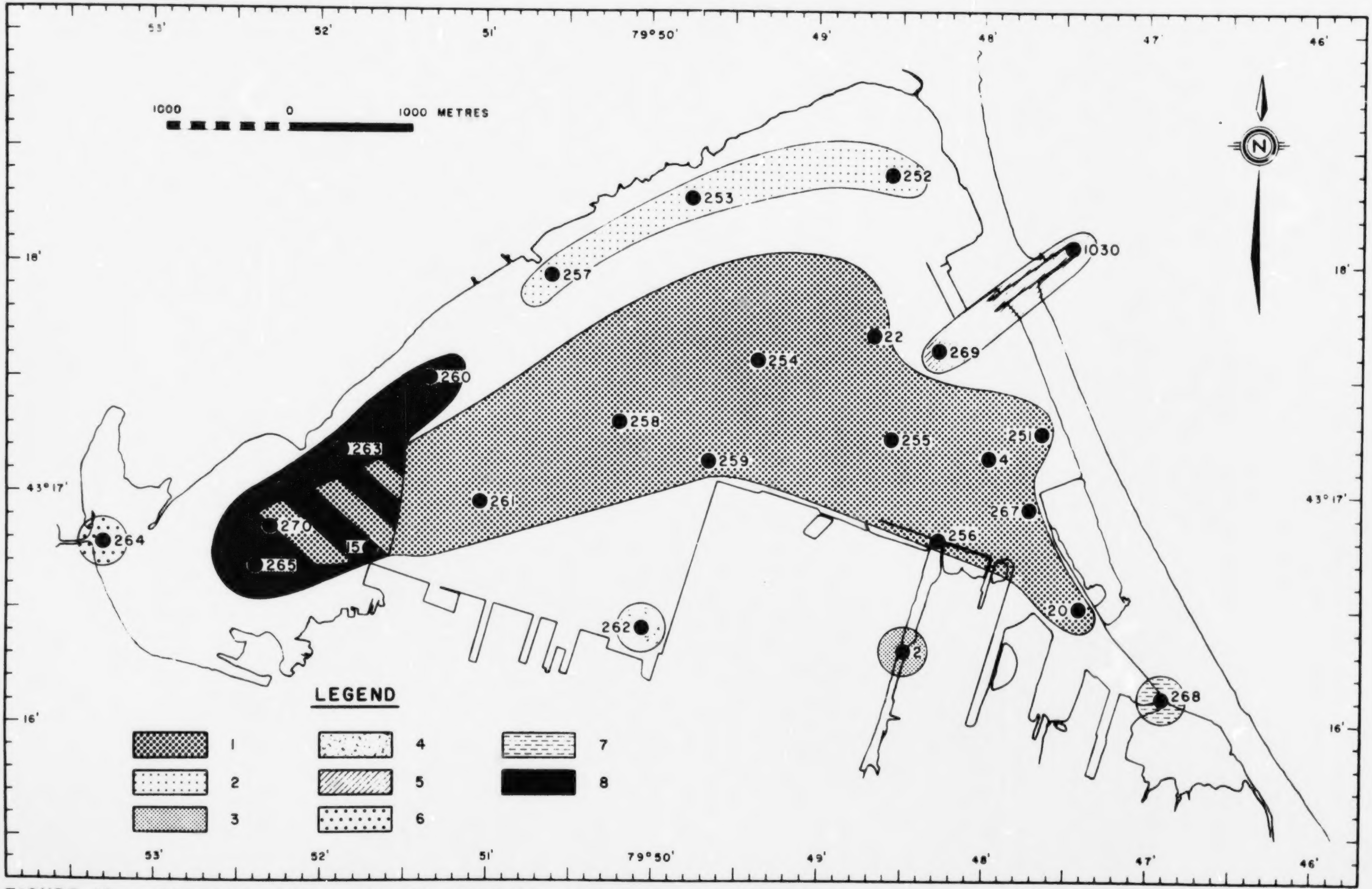
COMBINATION OF 1, 5 AND 6

FIGURE 9 - MAY 1977 HAMILTON HARBOUR SEDIMENTS, 8 FACTORS.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LEGEND
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FIGURE 10 – OCTOBER 1977 HAMILTON HARBOUR SEDIMENTS, 8 FACTORS.

HAMILTON HARBOUR STUDY

1977

VOLUME I

SECTION E

PHYTOPLANKTON AND BACTERIA

SUMMARY

Phytoplankton communites were numerically dominated by the *Chlorophyta* throughout most of the year. This position was briefly relinquished to the *Cryptophyta* during June. The *Bacillariophyceae* were sub-dominant throughout the year with peak column concentrations appearing in early July. Total cell densities were greatest during the spring. A second peak was observed during the summer and densities declined into the autumn. Maximum cell densities were invariably found in the upper few metres of the water column. These maxima coincided with the euphotic zone depth. Community structure was highly dynamic in the harbour, and interpretation of these fluctuations was confounded by the unstable physical regime and the diverse chemical loadings.

Determinations of specific bacterial populations showed that the heterotrophs were numerically dominant throughout the year. These were followed in decreasing densities by the sulphur oxidizers, nitrifiers, sulphur reducers and fecal coliforms. Population densities were polymodally distributed over the year and were both spatially and temporally heterogeneous. Density fluctuations were not simple correlates of substrate concentration, temperature or dissolved oxygen concentration. Although neither processes nor reaction rates can be ascertained from standing stocks, the extremely high densities of the heterotrophs and sulphur oxidizers suggest that the metabolic processes associated with these bacteria were the major sources of oxygen depletion in the harbour.

INTRODUCTION

Hamilton Harbour has been previously characterized as having a physically complex environment similar to other Great Lakes coastal zones. It has been further described as being hypereutrophic with respect to its nutrient concentrations (MOE, 1978). The vertically unstable environment combined with the high light attentuation of the harbour result in depressed algal productivity and biomass (MOE, 1978).

Previous studies have characterized the harbour as having very high bacterial standing crops (MOE, 1978). These studies have shown that the heterotrophic bacteria were present in the greatest densities followed in descending order by the sulphur oxidizers, *Nitrosomonas*, *Nitrobacter*, fecal coliforms and sulphur reducers.

The determination of simple relationships between population dynamics and environmental variables has not been possible, not only due to the highly dynamic environment, but also because of the diverse nature of the chemical loadings to the harbour. A more detailed analysis based on several years of data will be required to gain a greater knowledge of the factors governing algal and bacterial community dynamics.

PHYTOPLANKTON

Phytoplankton samples were collected weekly at station 258 from 0.2, 1.0, 3.0, 5.0, 10.0, 15.0, and 20.0 metre depths in order to examine vertical community, composition and dynamics (refer to Figure 1). Sampling was conducted from early May to mid-October. In addition to densities, cell volumes were determined according to the methods outlined in previous reports (MOE, 1978; 1977).

The phytoplankton communities were comprised of a three phyla: the Chlorophyta (greens), the Chrysophyta (diatoms) and the Cryptophyta. The phylum Cyanophyta (blue-greens) was also represented but only in very low densities at the end of the summer. In general, the number of cells per ml were greatest in the surface waters and declined with depth. Total cell densities were as great in the surface 3 m as they were in the remaining 17m. This concentration of cells within the first few meters of the water column was expected since the euphotic zone depth (the depth at which the irradiance is 1% of the surface level) was previously ascertained to be approximately 4 m (MOE, 1978). There was however a surprisingly high density of cells at the 20 m depth throughout the year (refer to Table 1). This high bottom concentration was likely the result of the diffuse and transient thermal structure present in 1977 (refer to Figure 3, Section A). These temperature profiles show that the classical thermocline conditions of 1^0C change of temperature per metre depth were found very infrequently. Therefore exchanges of mass and energy between surface and bottom waters may have occurred repeatedly.

The Chlorophyta comprised most of the biomass throughout the whole of the column during the spring. Tetrastrum sp., Shroederia sp. and Chlamydamonas spp. were the most abundant green algae. The cryptophytes were the next most prevalent group with Rhodomonas minuta and Cryptomonas ovata being the only members found. Diatoms such as Stephanodiscus astrea, Synedra ulna and Asterionella formosa were also present but in low densities. During the early summer the cryptophytes attained numerical dominance, but by mid-July the green algae, such as Oocystis borgei, Pediastrum boryanum and Chlamydamonas sp. were once again present in the greatest densities (refer to Table 1).

The diatoms, which were always numerically inferior, were trimodally distributed. Peak column densities occurred in July with smaller peaks in May and August. The general trends for the population densities throughout the water column were similar to those observed in the surface metre (see Figures 2, 3 and 4). The total column diatom densities appear to be inversely correlated with the average water column contents of silica (Figure 5). All of the four major stations have approximately the same trend in their average column dissolved reactive silica contents (refer to Figure 5).

Total cell volumes throughout the water column were greatest during the early and late summer. They also appear to be correlated with temperature structure since they declined rapidly below thermal structures (refer to Figures 6, 7 and 8).

BACTERIA

Bacteria samples were collected bi-weekly at the four major sampling stations (Figure 1). In addition to the health hazard indicator organisms (fecal coliforms), nutrient cycle bacteria associated with sulphur, nitrogen and carbon were also examined. Standing stocks of the various species were measured at several depths from late April until mid-October.

In 1977, the heterotrophs, which utilize organic carbon, were the numerically dominant group. The sulphur oxidizing populations, which oxidize reduced forms of sulphur to sulphate, were the next most prevalent group. They were present at densities approximately one order of magnitude less than the heterotrophs. The Nitrosomonas and Nitrobacter populations, which convert ammonia to nitrite and nitrite to nitrate, were in total one order of magnitude less than the sulphur oxidizers. Their numbers in turn, were approximately an order of magnitude greater than the sulphur reducers and fecal coliforms, which were present in about equal densities (refer to Table 2). Although processes and reaction rates cannot be accurately assessed from standing stocks, these results do suggest that organic carbon breakdown and sulphur oxidation were the major sources of the large and sustained water column oxygen demand.

Heterotroph densities were greatest at the surface and declined with depth (figures 9, 10, 11, 13, 14, 15, 16, 17, 18 and 19), except at station 252, which showed vertically homogeneous distributions (figures 12 and 13). Station 4 had the largest annual geometric mean, followed in descending order by stations 252, 258 and 270. The populations were polymodally distributed at all depths over the year.

The sulphur oxidizer populations, in general, declined with depth and were also polymodally distributed at all depths over the year (figures 9 through 19). The annual geometric means showed that the greatest population densities were at station 4, followed by stations 252, 258 and 270 (Table 2).

The sulphur reducer populations, which were at least four orders of magnitude smaller than the sulphur oxidizers, showed slightly elevated surface concentrations (figures 9 through 19). These populations also showed polymodal density distributions. The population fluctuations were not directly correlated with those of the sulphur oxidizers.

Nitrosomonas populations showed irregular depth distributions (figures 9 through 19). Population densities showed mid-summer and late summer or early autumn peaks. The greatest densities were found at stations 258 and 270. The Nitrobacter populations were greater than or equal to the Nitrosomonas densities. Population sizes were in general greater at the bottom. Densities were greatest at station 270, followed by stations 258, 252 and 4.

The annual geometric means showed that the fecal coliform levels were slightly elevated over those of 1976 (Table 2). Densities frequently exceeded the 100 counts per 100 ml guideline for recreational waters. Coliform levels were generally greater at station 4, followed by station 252. Stations 258 and 270 had approximately equal population densities, which were also less than those of station 252 (figures 9 through 19). These populations were also polymodally distributed over the year.

Population size is unlikely to be uniquely correlated with a single environmental parameter but rather a function of a multivariate environment. The major variables are most likely temperature, dissolved oxygen concentration, and substrate concentration.

References

Ontario Ministry of the Environment, 1977. Hamilton Harbour Study, 1975. Water Resources Branch, 135 St. Clair Avenue West, Toronto.

Ontario Ministry of the Environment, 1978. Hamilton Harbour Study, 1976. Water Resources Branch, 135 St. Clair Avenue West, Toronto.

Table 2: Bacterial Populations of Hamilton Harbour - 1977
(Annual Geometric Means), Counts/100 mL

	Surface	Middle	Bottom
	Station #4		
Fecal Coliforms	179	88	35
Heterotrophs	26,228,500	7,783,400	6,709,700
Sulphur Oxidizers	1,947,745	704,252	117,728
Sulphur Reducers	217	25	66
Nitrosomonas	6,348	3,950	5,247
Nitrobacter	2,467	2,780	5,041
	Station #252		
Fecal Coliforms	48	-	96
Heterotrophs	14,803,900	-	14,984,100
Sulphur Oxidizers	315,899	-	86,341
Sulphur Reducers	212	-	274
Nitrosomonas	4,051	-	8,919
Nitrobacter	3,100		8,028
	Station #258		
Fecal Coliforms	68	31	18
Heterotrophs	10,736,600	4,905,800	4,110,600
Sulphur Oxidizers	204,853	73,206	151,287
Sulphur Reducers	26	18	19
Nitrosomonas	3,400	10,638	21,175
Nitrobacter	5,636	5,462	4,720
	Station #270		
Fecal Coliforms	49	61	22
Heterotrophs	8,665,000	5,300,500	5,122,900
Sulphur Oxidizers	29,351	40,554	456
Sulphur Reducers	47	24	16
Nitrosomonas	2,700	4,052	21,500
Nitrobacter	6,608	5,003	18,473

Table 1: Phytoplankton Densities (cells/mL) at Station 258

Depth (m)	Class	May 11	May 17	May 25	June 8	June 15	June 21	July 5	July 13	July 20	July 26	Aug. 2	Aug. 10	Aug. 19	Aug. 23	Aug. 30	Sept. 7	Sept. 19	Oct. 14
0.2	Cryptophyta	1,250	8,631	2242	1204	1030	854	524	41	244	286	206	3032	270	304	284	766	168	294
	Bacillariophyceae	94	46	-	2	26	54	212	99	40	42	74	152	160	144	78	72	90	60
	Chlorophyta	25,441	17,057	4189	30	48	30	920	1172	1696	2255	1468	1188	925	620	458	1128	494	242
	Cyanophyta	-	-	-	-	-	-	-	-	-	-	-	-	-	10	8	30	16	18
	TOTAL	26,785	25,734	6431	1236	1104	938	1656	1312	1980	2583	1748	4372	1357	1048	828	1996	765	614
1.0	Cryptophyta	-	6,286	3641	1142	838	910	412	159	204	252	100	2662	442	318	384	776	70	170
	Bacillariophyceae	-	32	-	8	36	60	276	98	26	50	64	140	110	88	126	90	100	74
	Chlorophyta	-	12,708	4884	22	12	52	1464	969	2792	1802	1210	1048	634	655	704	1138	252	259
	Cyanophyta	-	-	-	-	-	-	-	-	-	-	-	-	-	2	4	16	18	32
	TOTAL	-	19,026	8525	1132	894	1022	2152	1226	3022	2104	1374	3850	1190	1063	1218	2020	440	535
3.0	Cryptophyta	-	7,202	1964	1042	742	486	60	157	-	262	190	828	-	406	-	6	94	224
	Bacillariophyceae	-	26	-	10	34	70	462	104	-	62	96	162	-	150	-	24	92	94
	Chlorophyta	-	13,648	5707	18	20	80	1196	1263	-	2311	1559	1304	-	585	-	70	156	292
	Cyanophyta	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	12	22
	TOTAL	-	20,876	7671	2060	796	634	1664	1524	-	2635	1845	2294	-	1242	-	106	354	632
5.0	Cryptophyta	-	2,187	394	1122	130	144	28	26	4	192	150	1783	144	344	172	530	114	180
	Bacillariophyceae	-	44	4	26	36	100	464	157	74	42	110	114	126	144	118	108	108	60
	Chlorophyta	-	9,701	5269	34	12	62	508	773	858	1970	1387	1058	468	565	767	1316	312	230
	Cyanophyta	-	-	-	-	-	-	2	-	-	-	-	-	-	18	20	22	16	16
	TOTAL	-	11,932	5663	1182	178	306	1002	965	936	2204	1647	2955	746	1071	1177	1976	550	486
10.0	Cryptophyta	-	30	134	82	140	32	-	126	196	6	4	64	-	22	-	36	-	222
	Bacillariophyceae	-	52	4	8	14	36	388	199	42	8	24	150	122	138	114	78	104	50
	Chlorophyta	-	11,816	8	10	14	12	160	1302	1866	298	553	842	365	430	78	418	340	226
	Cyanophyta	-	-	-	-	-	-	-	-	-	-	-	-	-	4	-	8	22	20
	TOTAL	-	11,902	142	100	168	80	548	1627	2104	312	581	1056	748	594	112	540	466	518
15.0	Cryptophyta	-	16	20	8	68	6	8	-	4	12	-	76	-	360	6	-	-	126
	Bacillariophyceae	-	82	2	2	18	28	114	25	32	36	12	38	106	130	146	-	-	60
	Chlorophyta	-	15,374	8	8	8	12	188	50	44	134	354	600	126	441	278	-	-	260
	Cyanophyta	-	-	-	-	-	-	2	-	-	-	-	-	-	2	-	-	-	26
	TOTAL	-	15,474	23	18	94	46	312	75	80	182	366	714	232	933	430	-	-	472

Continuation Table 1

Depth (m)	Class	DATE																	
		May 11	May 17	May 25	June 8	June 15	June 21	July 5	July 13	July 20	July 26	Aug. 2	Aug. 10	Aug. 19	Aug. 23	Aug. 30	Sept. 7	Sept. 19	Oct. 14
	Cryptophyta	-	2	204	-	18	20	12	-	26	4	-	16	-	4	-	18	-	-
	Bacillariophyceae	-	154	14	-	12	4	256	477	54	22	-	42	-	22	84	38	-	-
20.0	Chlorophyta	-	18,746	24	-	2	-	148	142	216	304	-	382	-	42	138	208	-	-
	Cyanophyta	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	TOTAL	-	18,902	228	-	32	24	416	619	296	330	-	440	-	68	222	264	-	-
Column	TOTAL	26,785	17,692	4018	955	3239	436	1701	1050	1203	1479	1260	2240	855	860	661	1150	515	543
Average	Cryptophyta	1,250	3,479	1228	767	424	350	149	73	113	145	108	1204	171	251	141	355	89	203
	Bacillariophyceae	94	62	6	9	25	50	310	166	45	37	63	114	125	117	111	68	99	66
	Chlorophyta	25,441	14,150	2172	20	17	35	655	810	1245	1296	1088	917	502	491	404	713	311	251

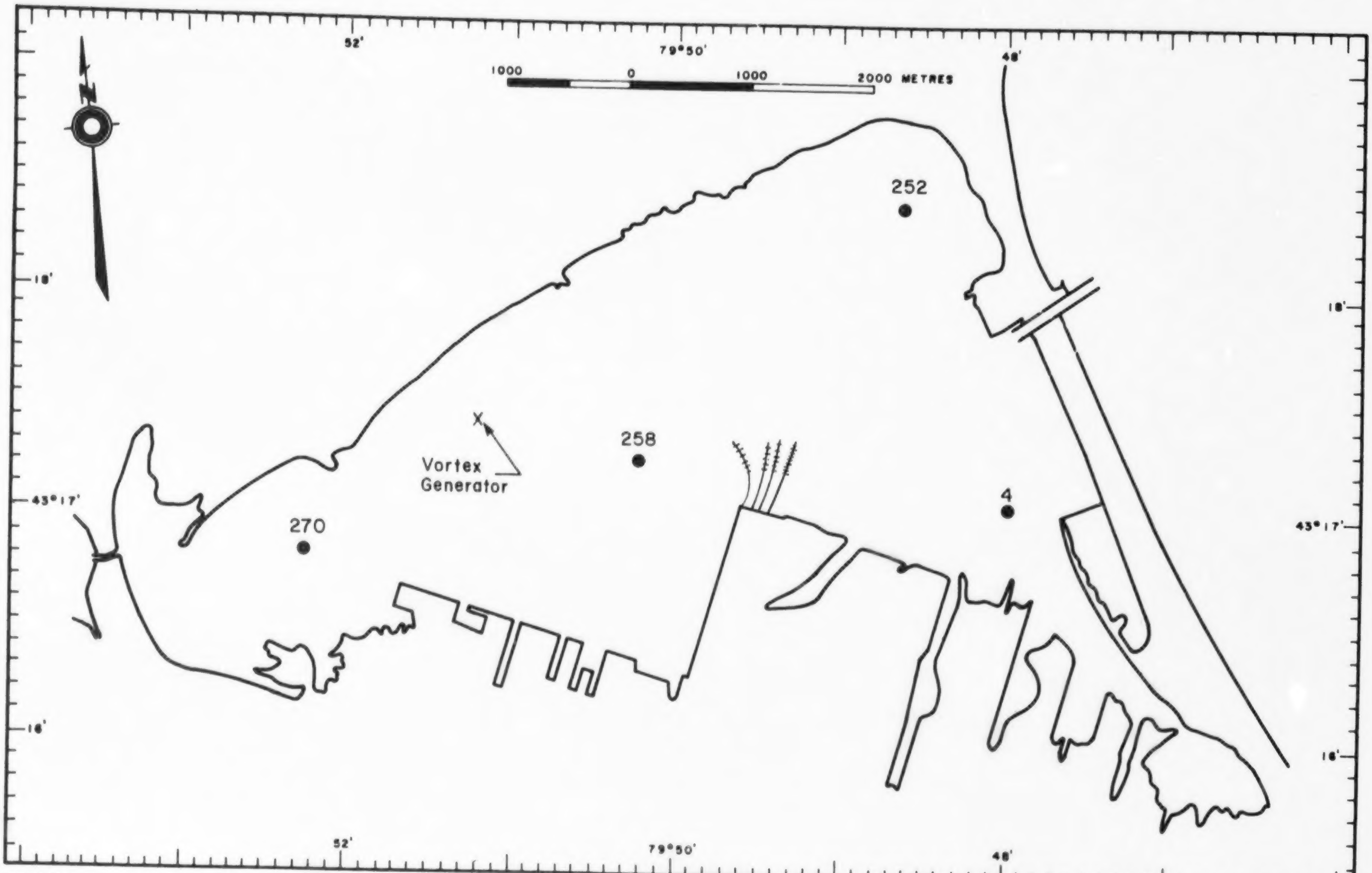
52'
79°50'
48'
1000
0
1000
2000 METRES
18'
43°17'
16'
252
258
270
4
Vortex
Generator
X

FIGURE 1 : HAMILTON HARBOUR ILLUSTRATING DIFFUSER LINE, POSITION OF VORTEX GENERATOR AND MAJOR SAMPLING STATIONS

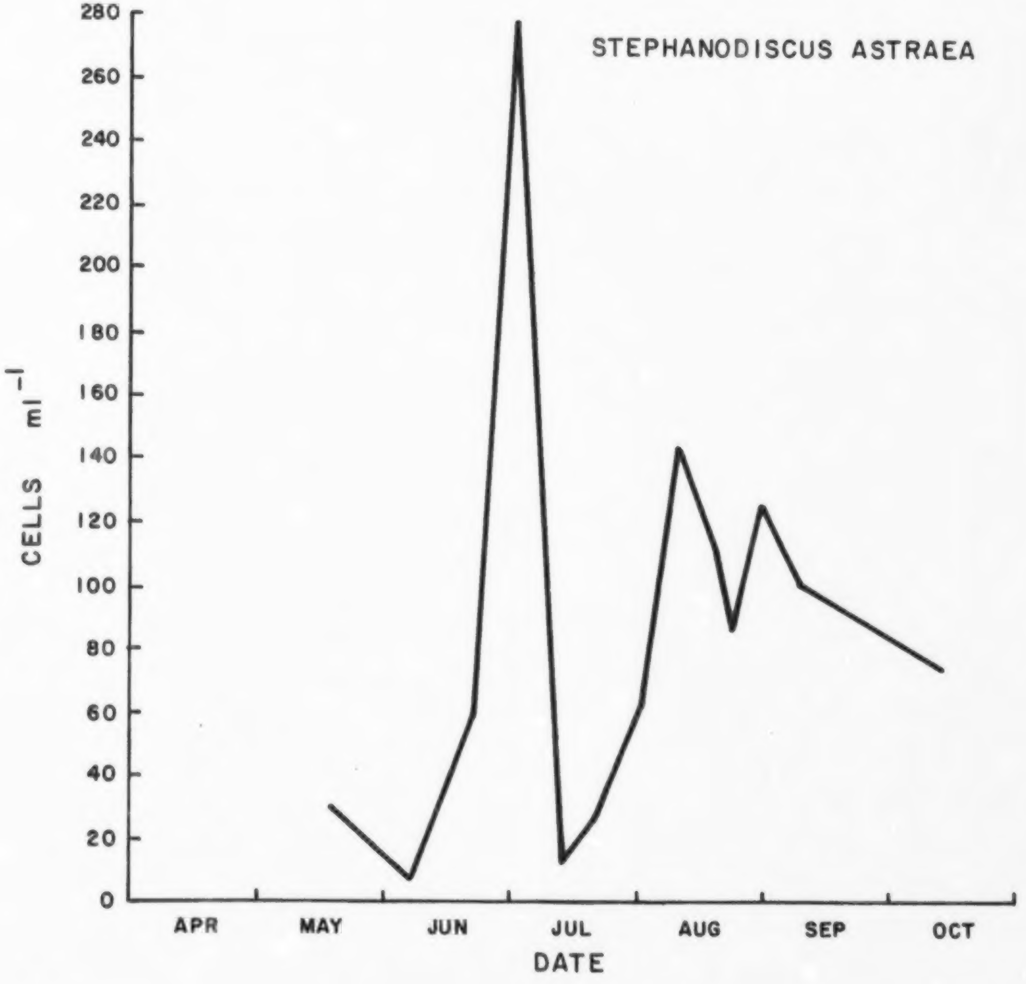

FIGURE 2 : TEMPORAL ABUNDANCE OF DIATOMS AT STATION 258 (1 m). HAMILTON HARBOUR 1977

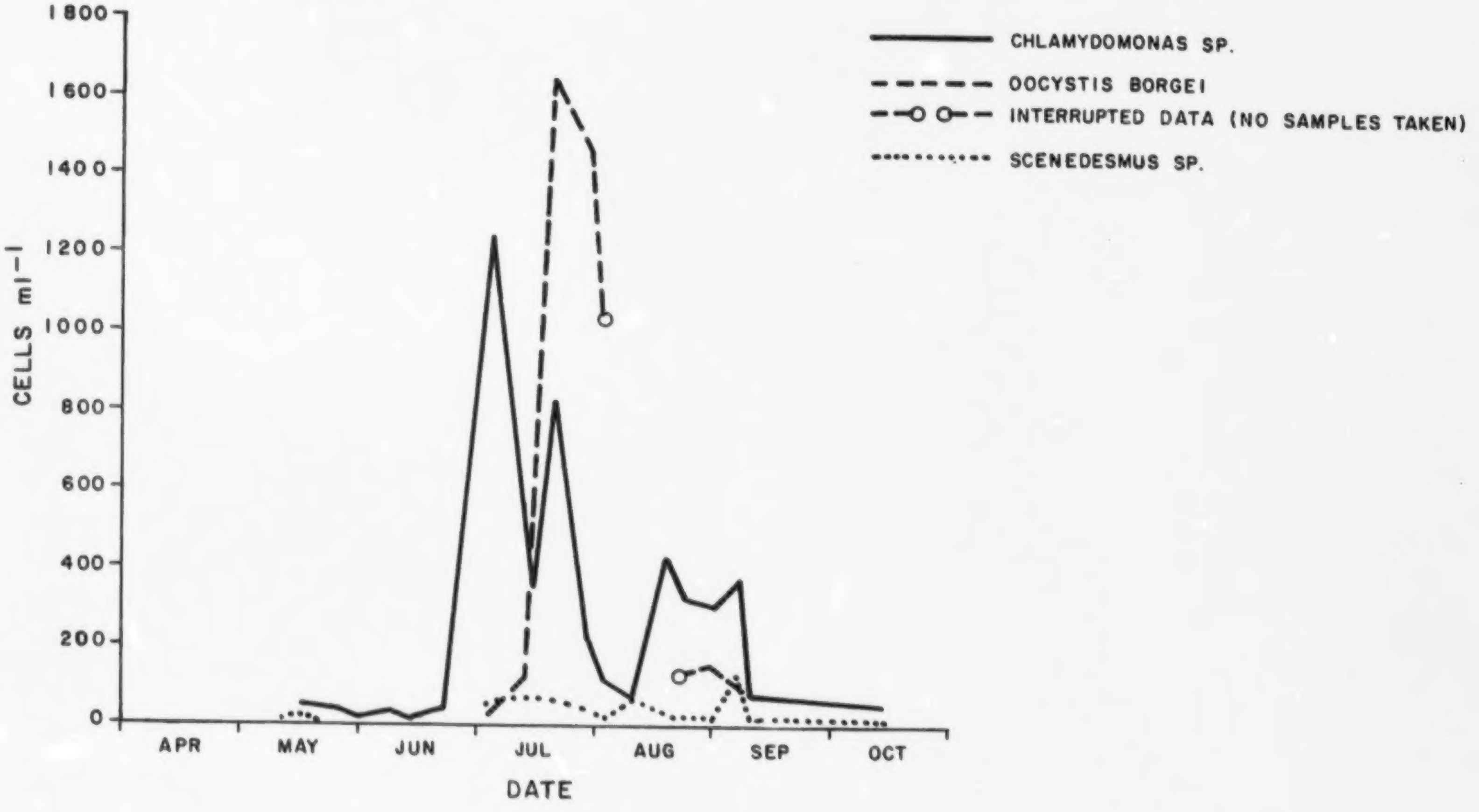

FIGURE 3 : TEMPORAL ABUNDANCE OF CHLOROPHYTA (Green Algae) AT STATION 258 (1m). HAMILTON HARBOUR 1977

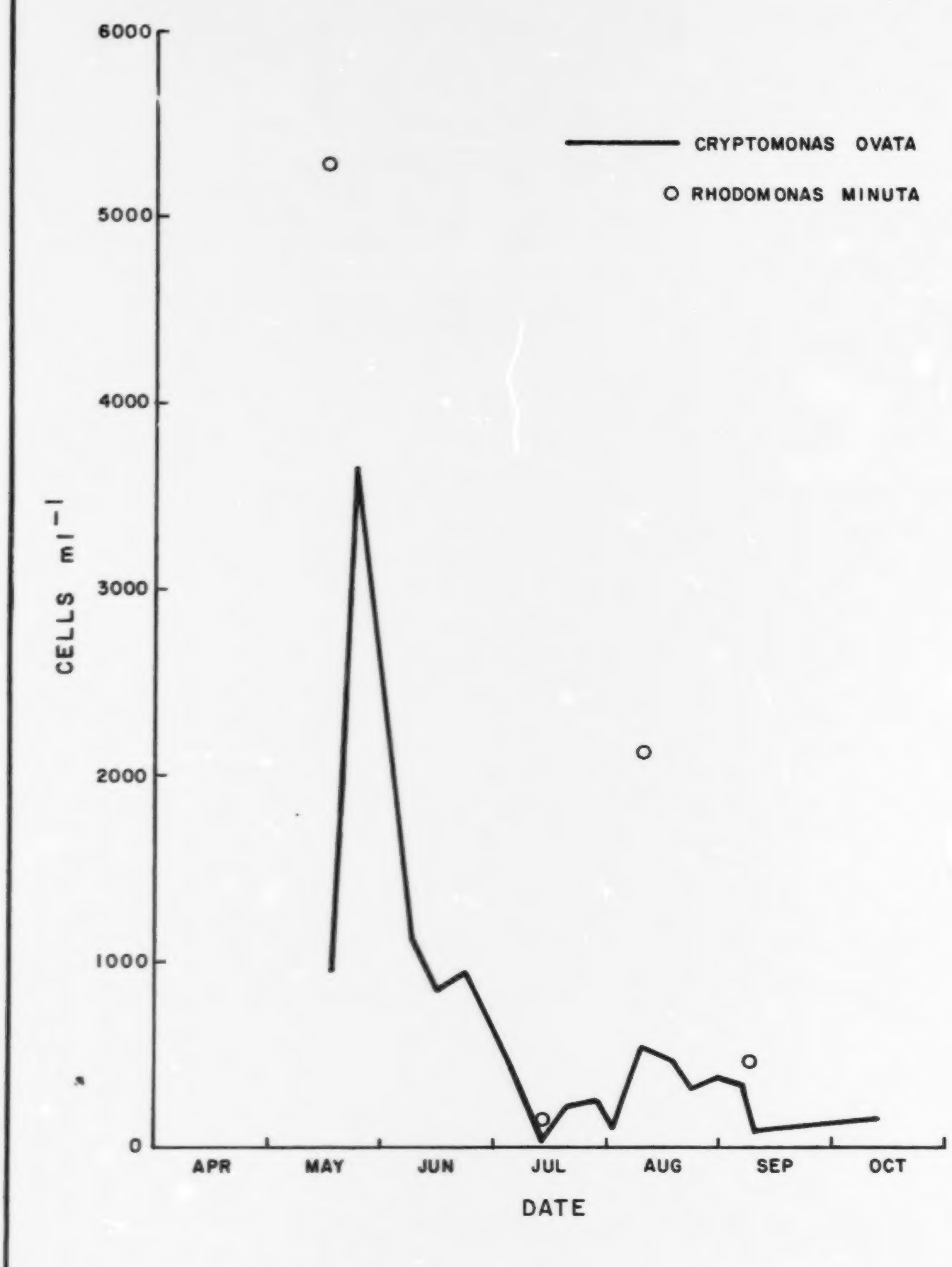

FIGURE 4 : TEMPORAL ABUNDANCE OF CRYPTOPHYTA AT STATION 258 (1m). HAMILTON HARBOUR 1977

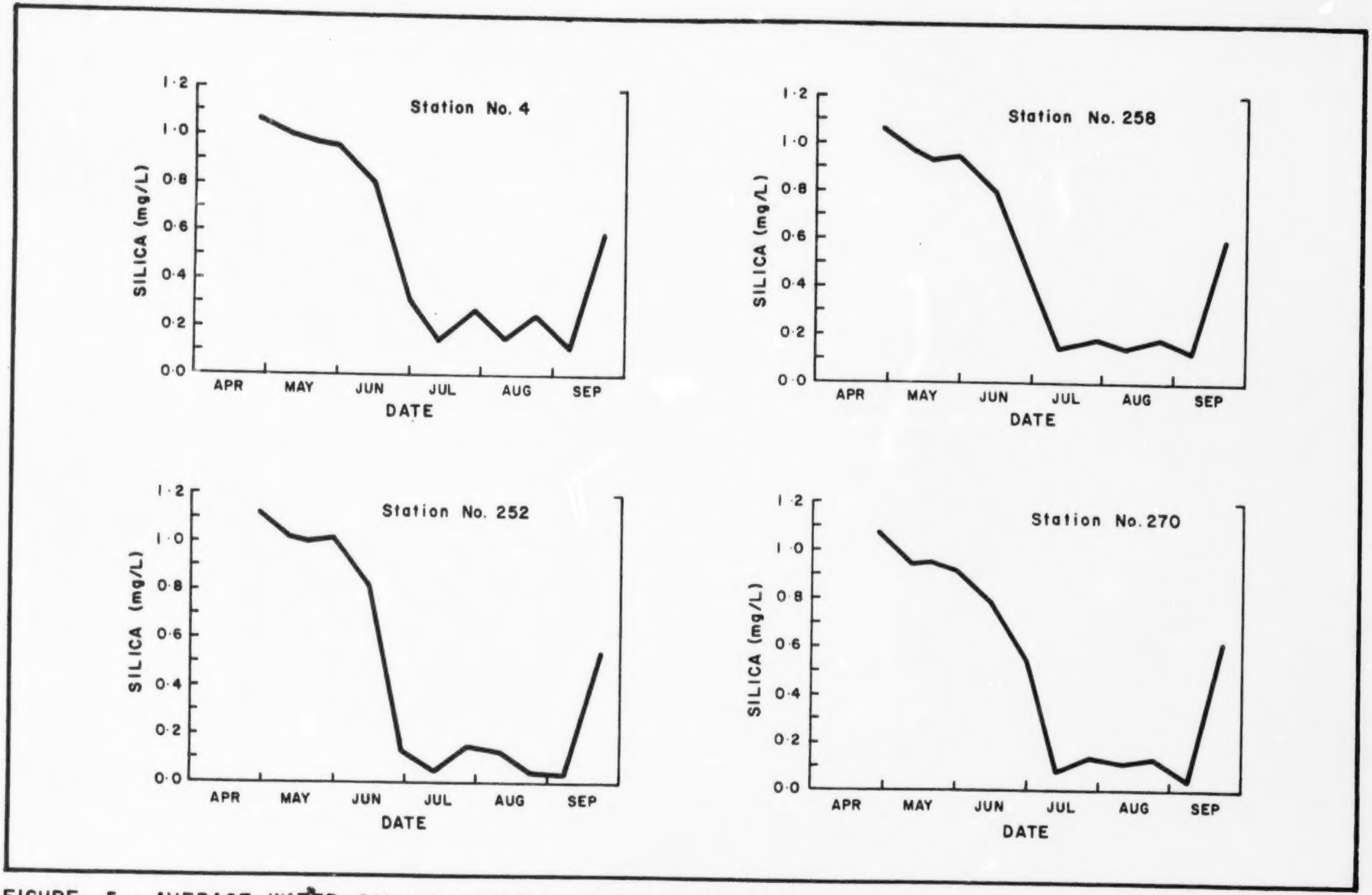

FIGURE 5 : AVERAGE WATER COLUMN CONTENT OF DISSOLVED REACTIVE SILICA 1977

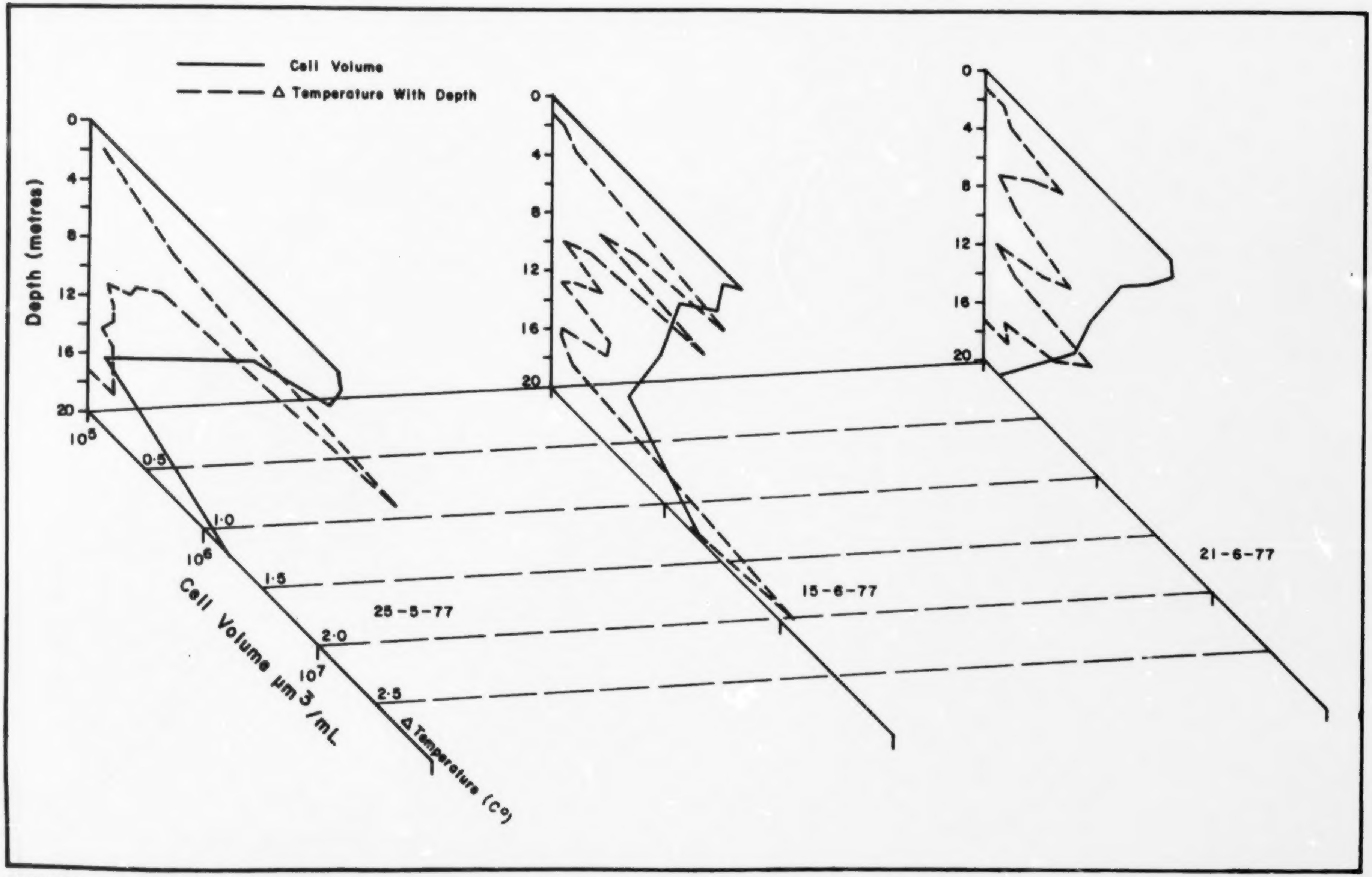

FIGURE 6 : TOTAL CELL VOLUMES AND TEMPERATURE STRUCTURE AT STATION 258

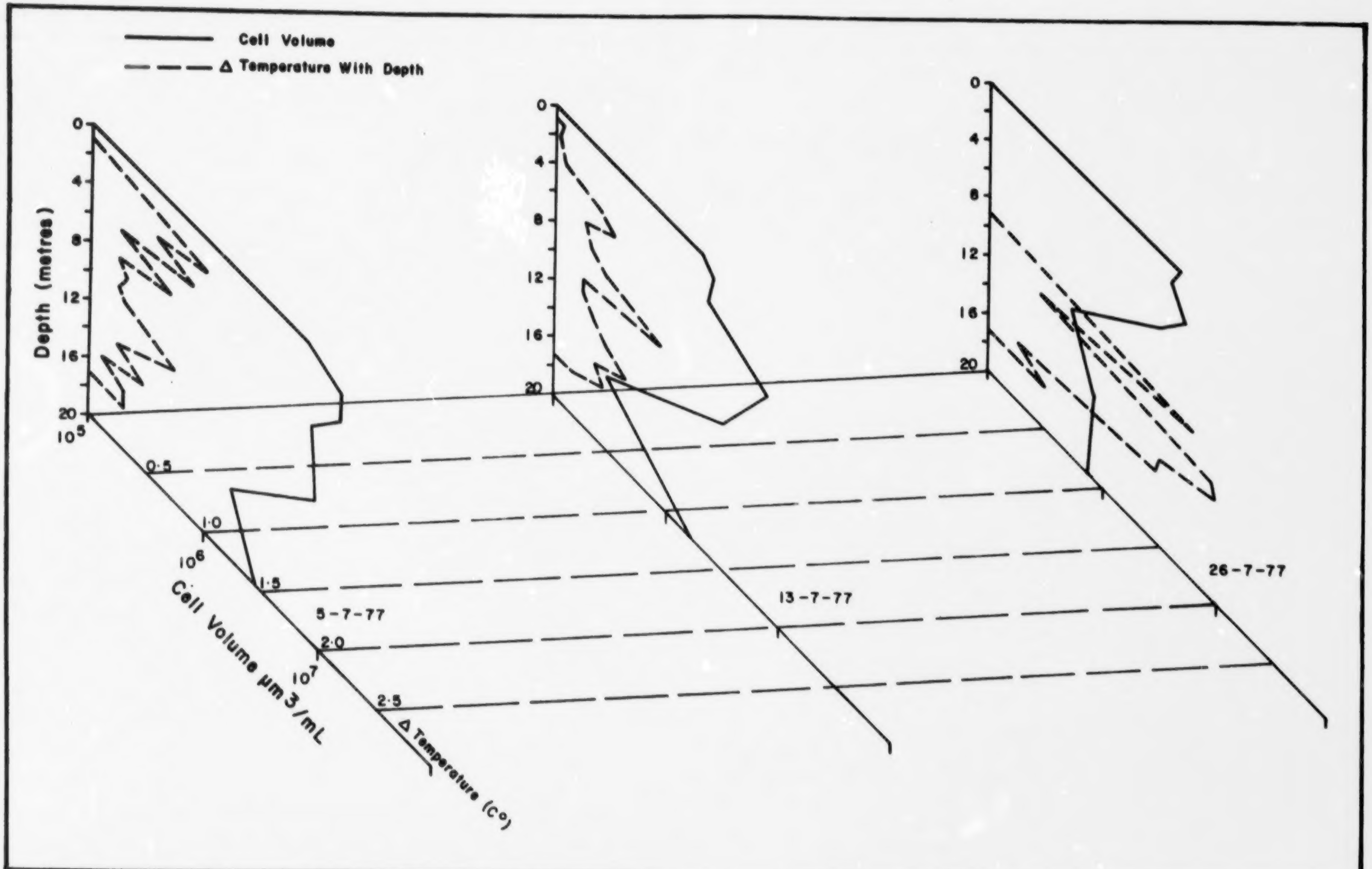

FIGURE 7 : TOTAL CELL VOLUMES AND TEMPERATURE STRUCTURE AT STATION 258

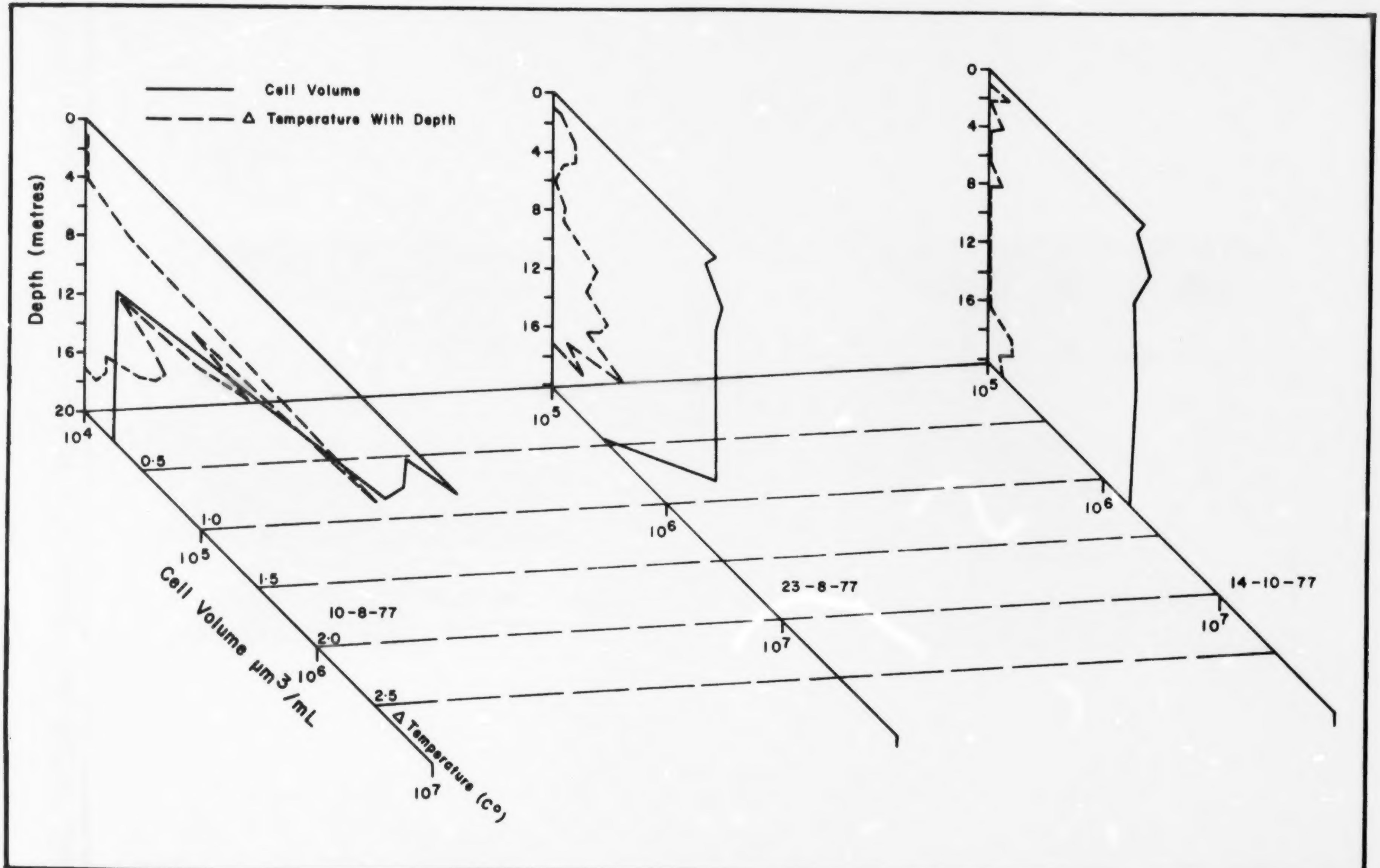

FIGURE 8 : TOTAL CELL VOLUMES AND TEMPERATURE STRUCTURE AT STATION 258

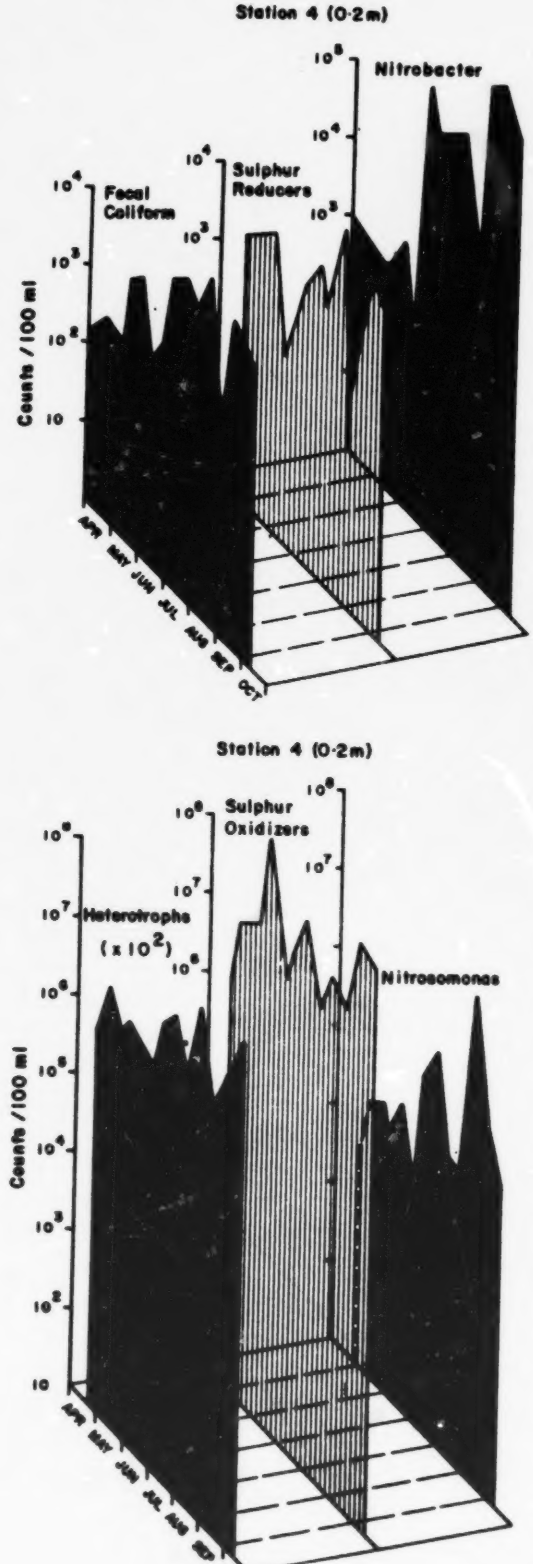

FIGURE 9: TEMPORAL ABUNDANCE OF BACTERIA IN HAMILTON HARBOUR 1977.

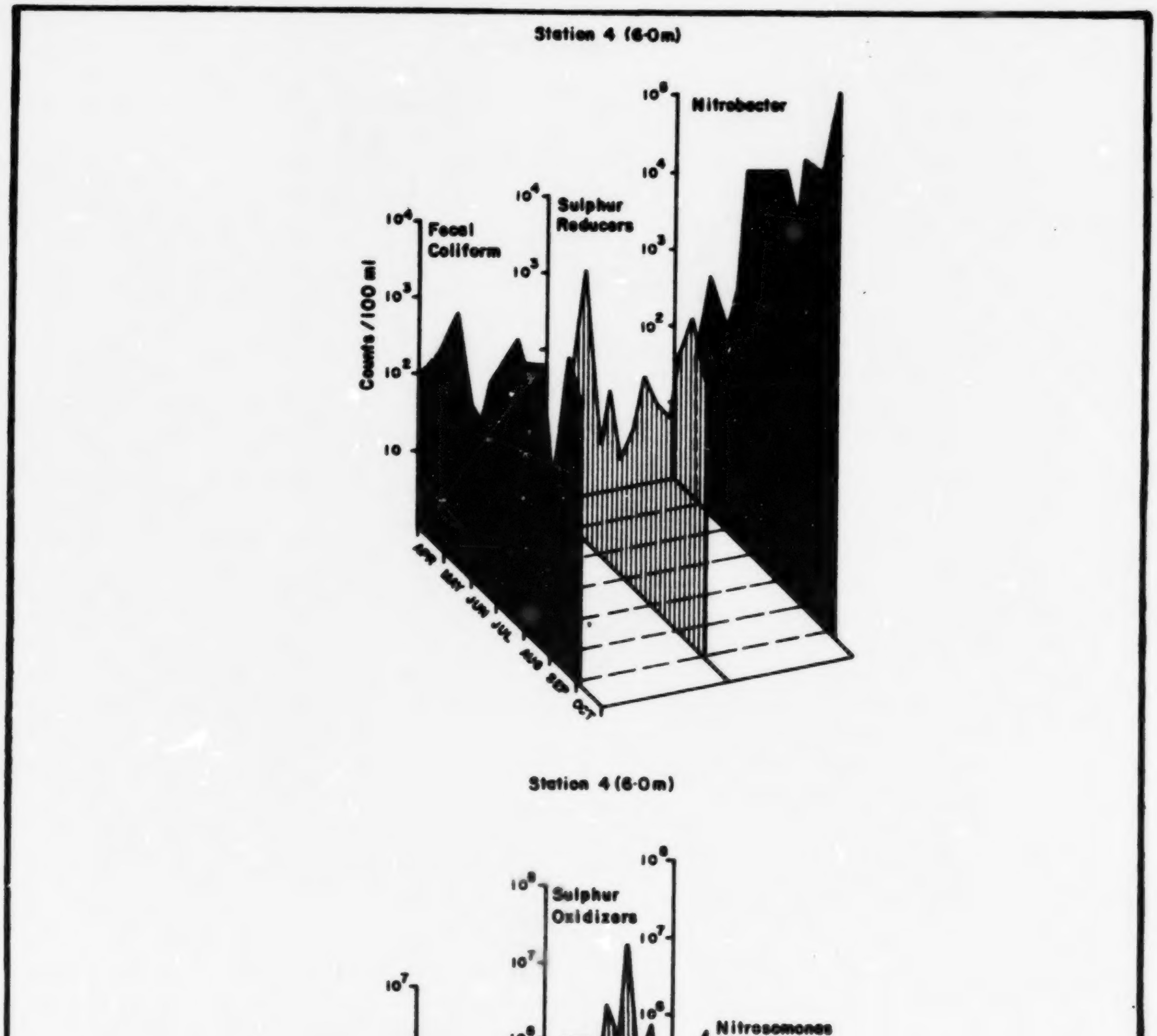

FIGURE 10 : TEMPORAL ABUNDANCE OF BACTERIA IN HAMILTON HARBOUR 1977.

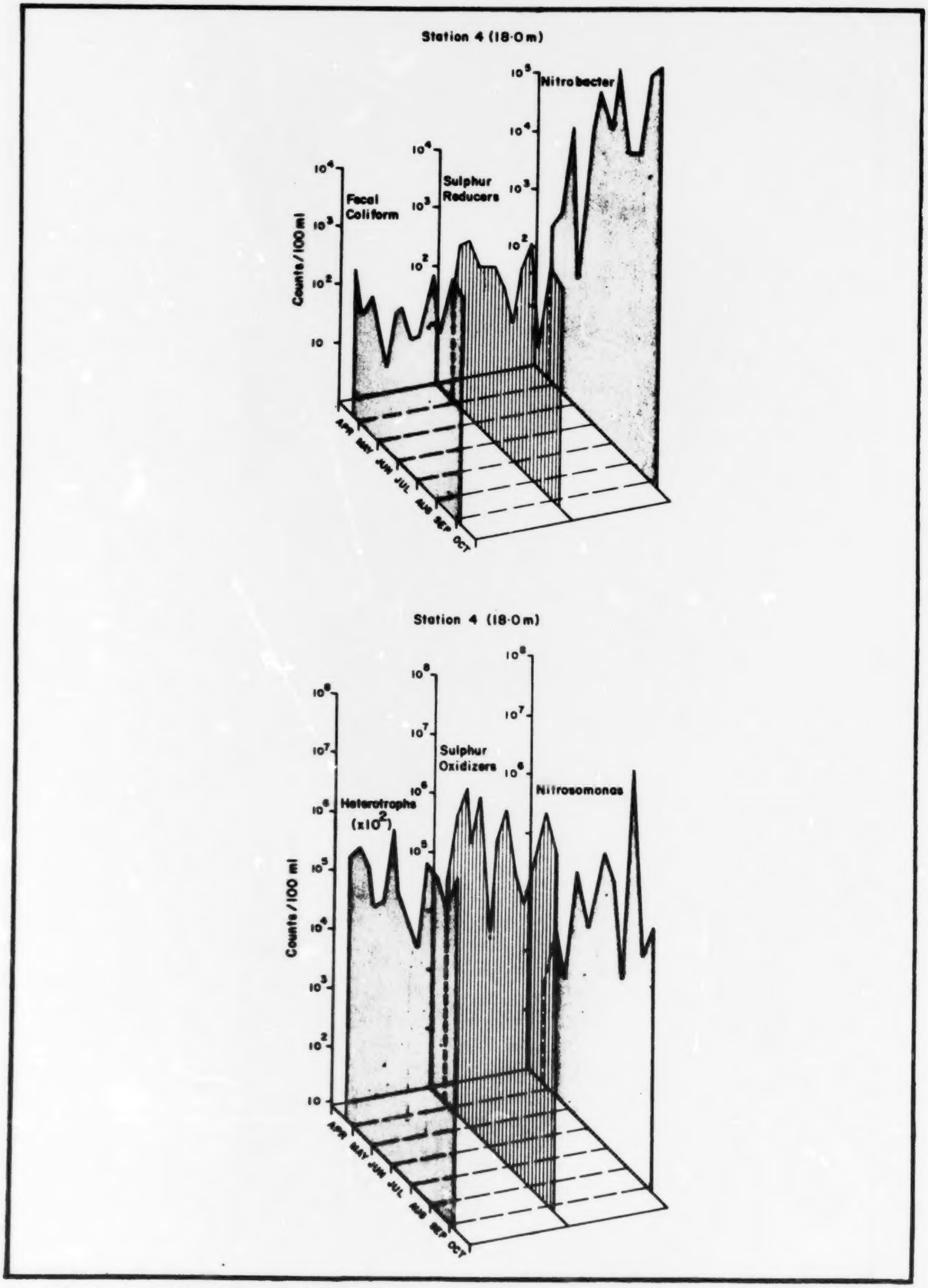

FIGURE 11 : TEMPORAL ABUNDANCE OF BACTERIA IN HAMILTON HARBOUR 1977.

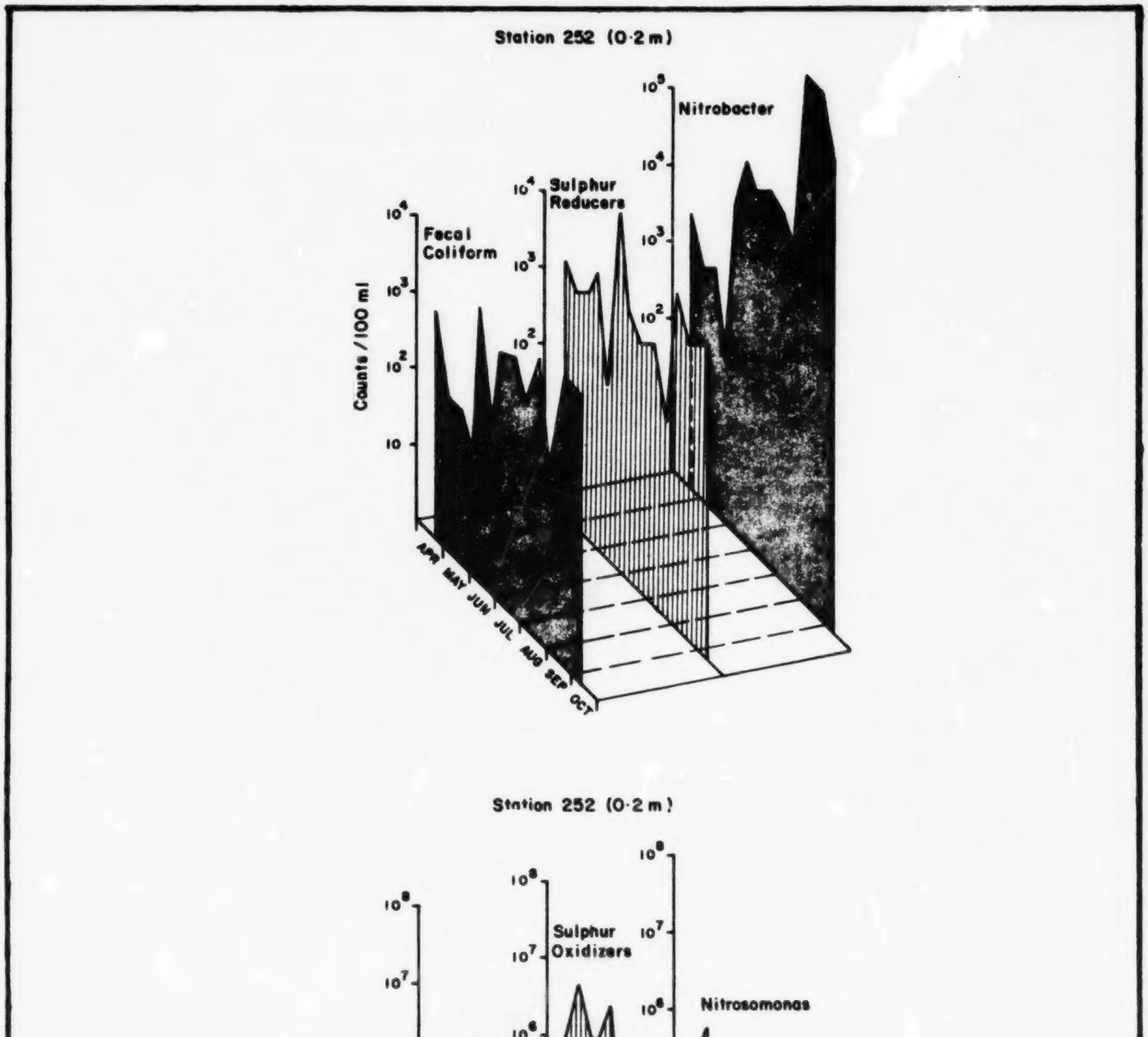

FIGURE 12 : TEMPORAL ABUNDANCE OF BACTERIA IN HAMILTON HARBOUR 1977.

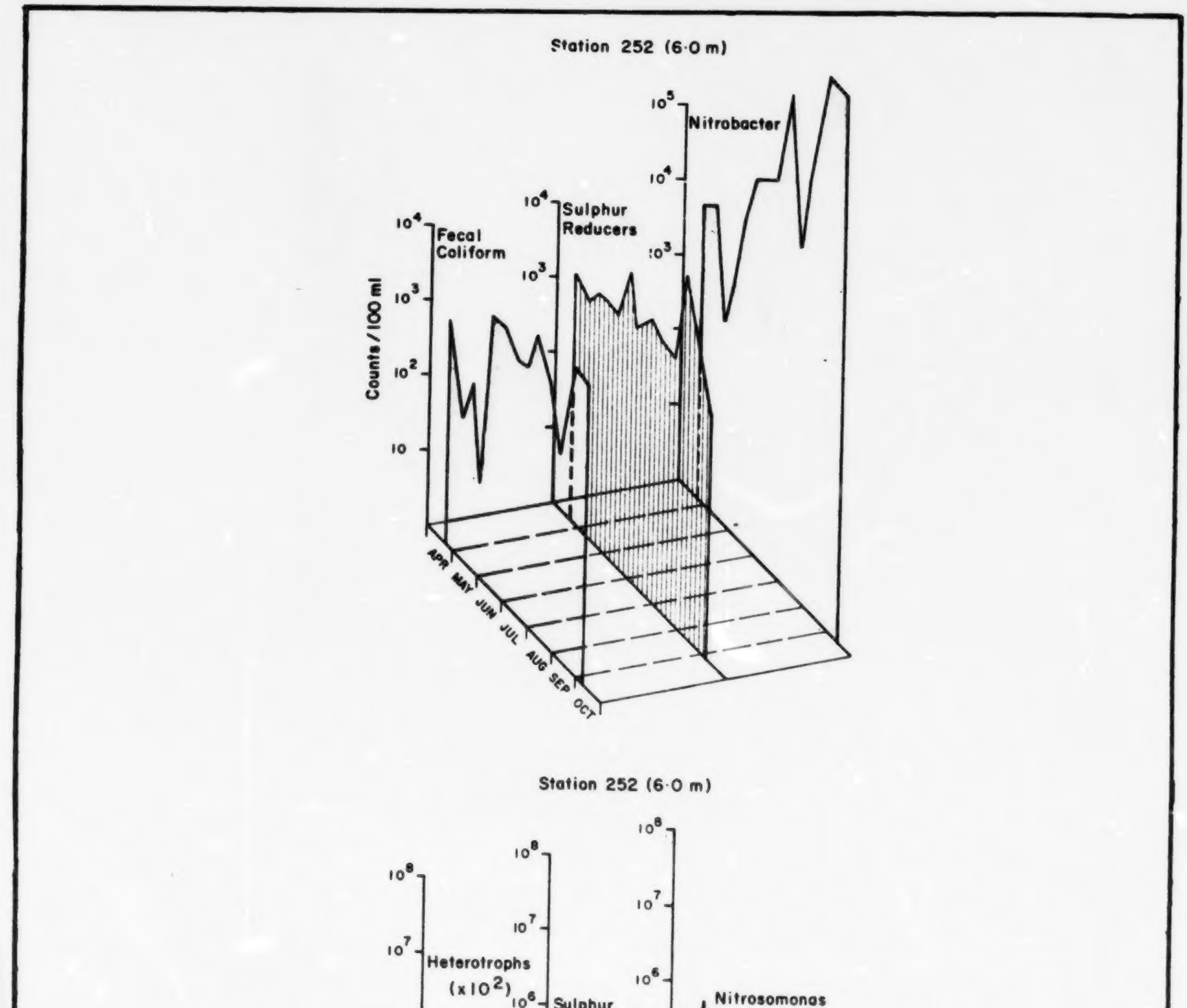

FIGURE 13 : TEMPORAL ABUNDANCE OF BACTERIA IN HAMILTON HARBOUR 1977.

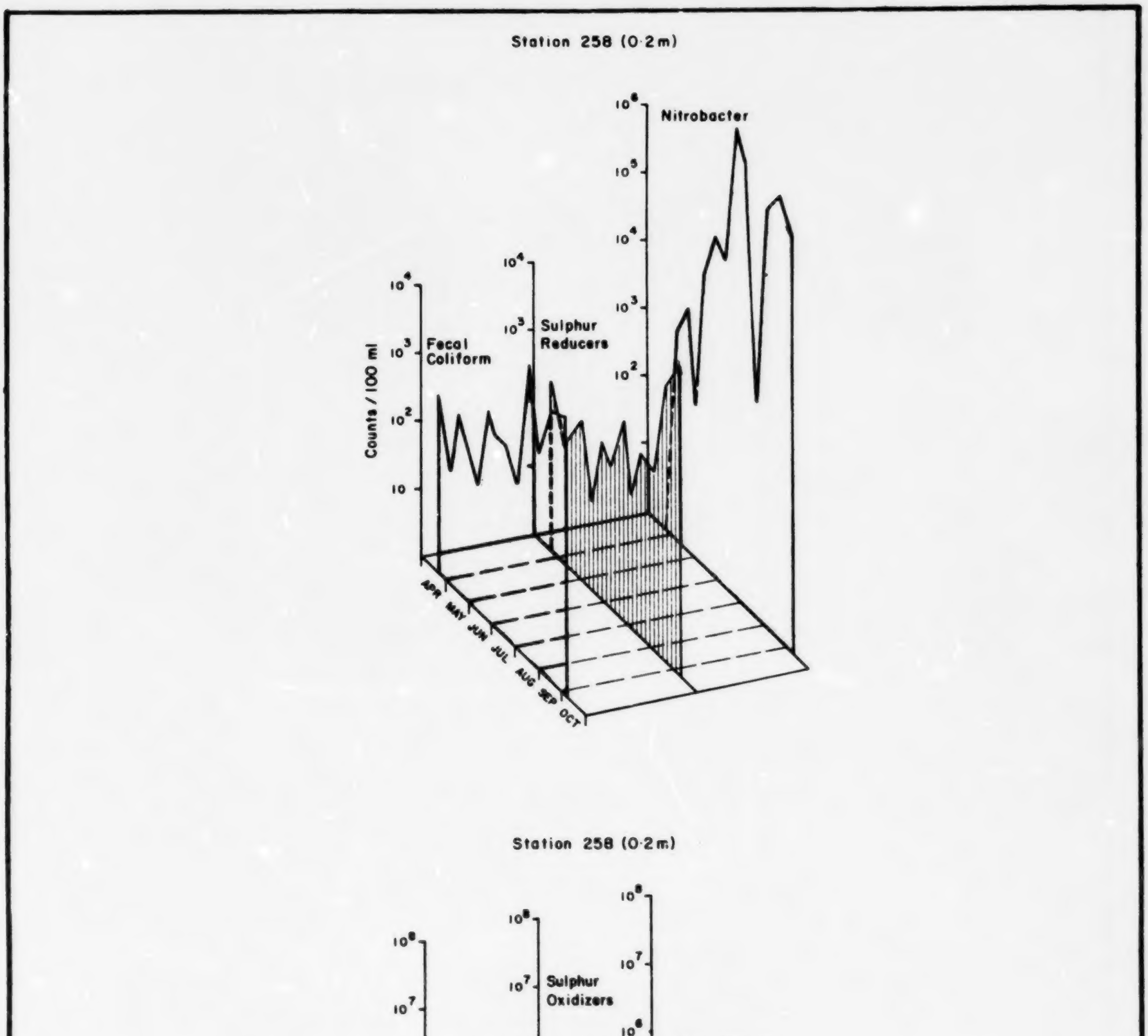

FIGURE 14 : TEMPORAL ABUNDANCE OF BACTERIA IN HAMILTON HARBOUR 1977.

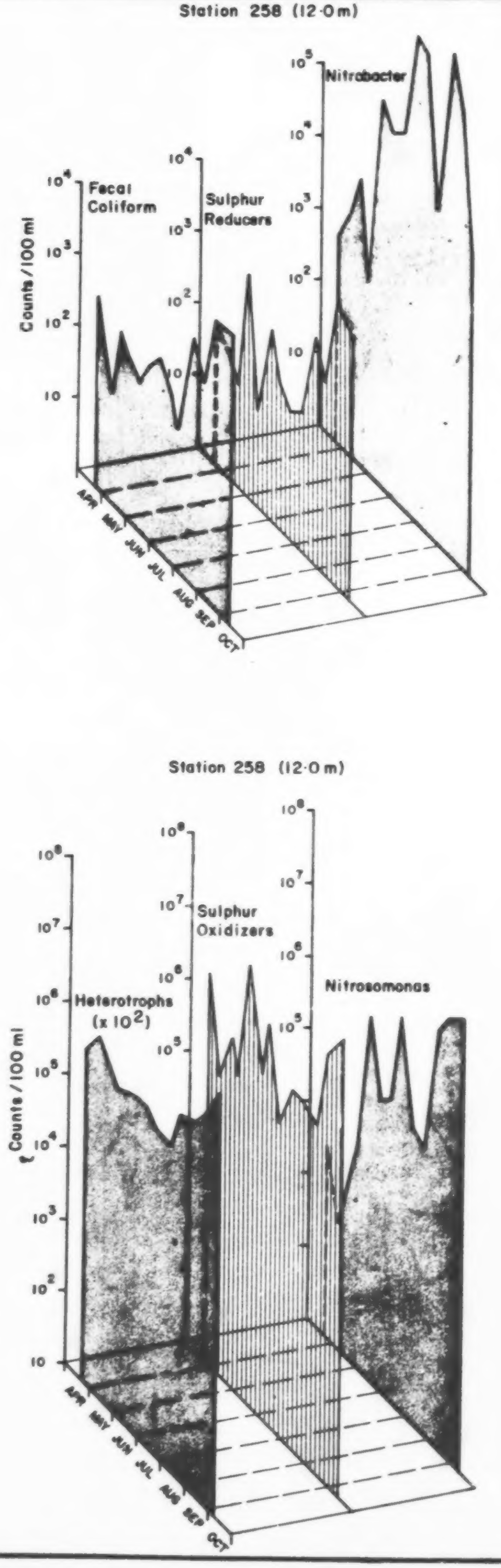

FIGURE 15 : TEMPORAL ABUNDANCE OF BACTERIA IN HAMILTON HARBOUR 1977.

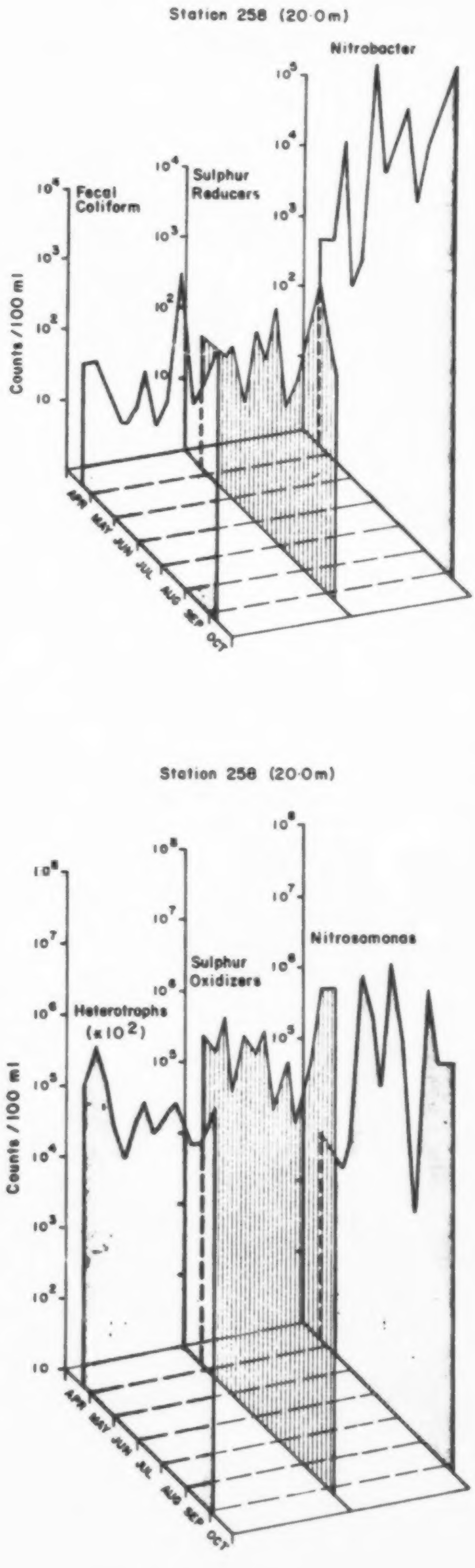

FIGURE 16 : TEMPORAL ABUNDANCE OF BACTERIA IN HAMILTON HARBOUR 1977.

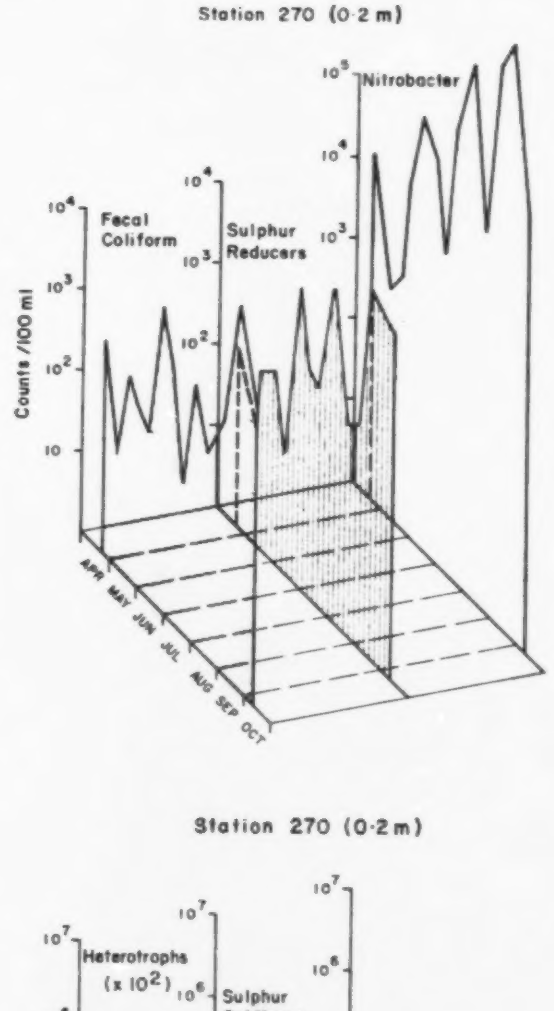

FIGURE 17 : TEMPORAL ABUNDANCE OF BACTERIA IN HAMILTON HARBOUR 1977.

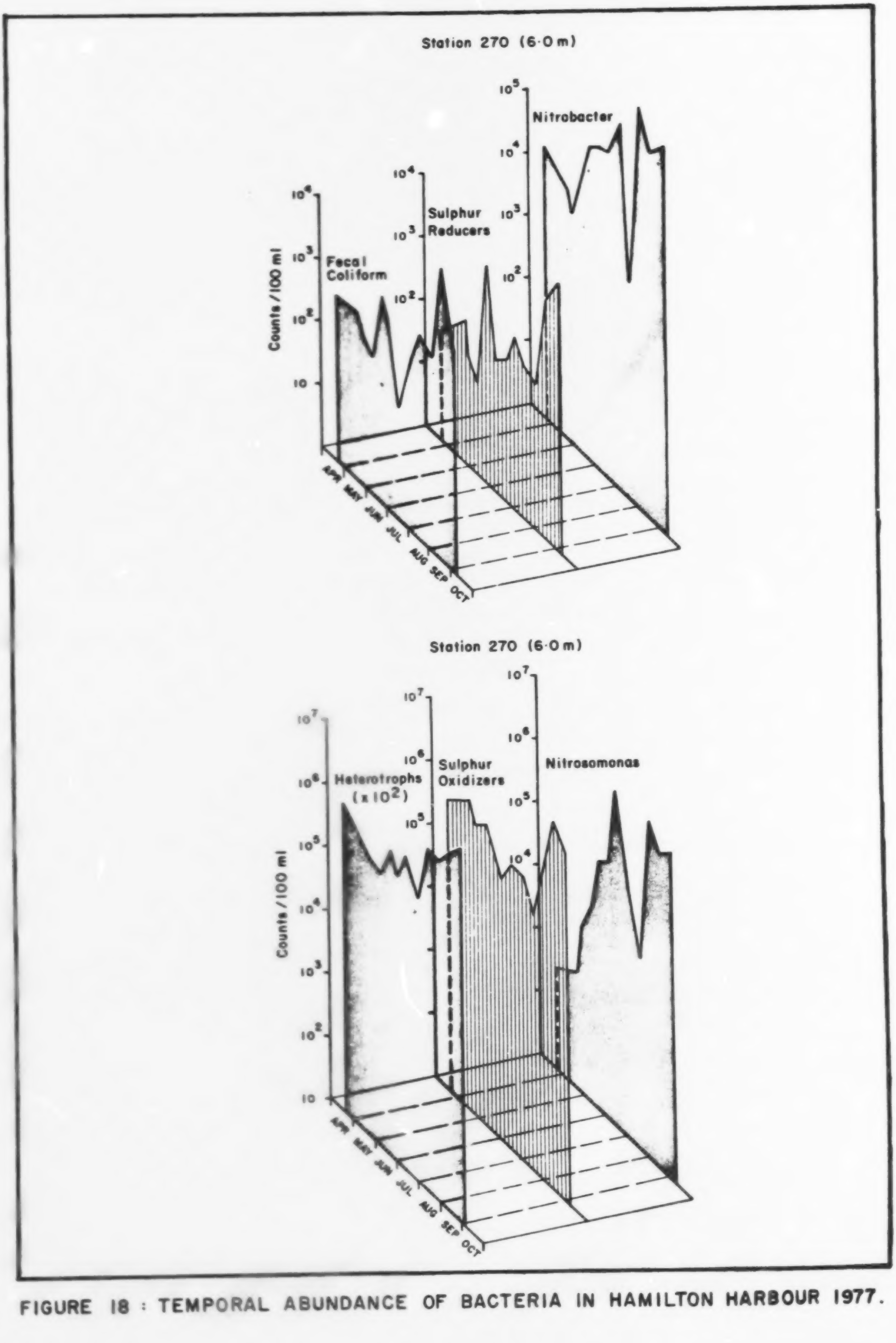

FIGURE 18 : TEMPORAL ABUNDANCE OF BACTERIA IN HAMILTON HARBOUR 1977.

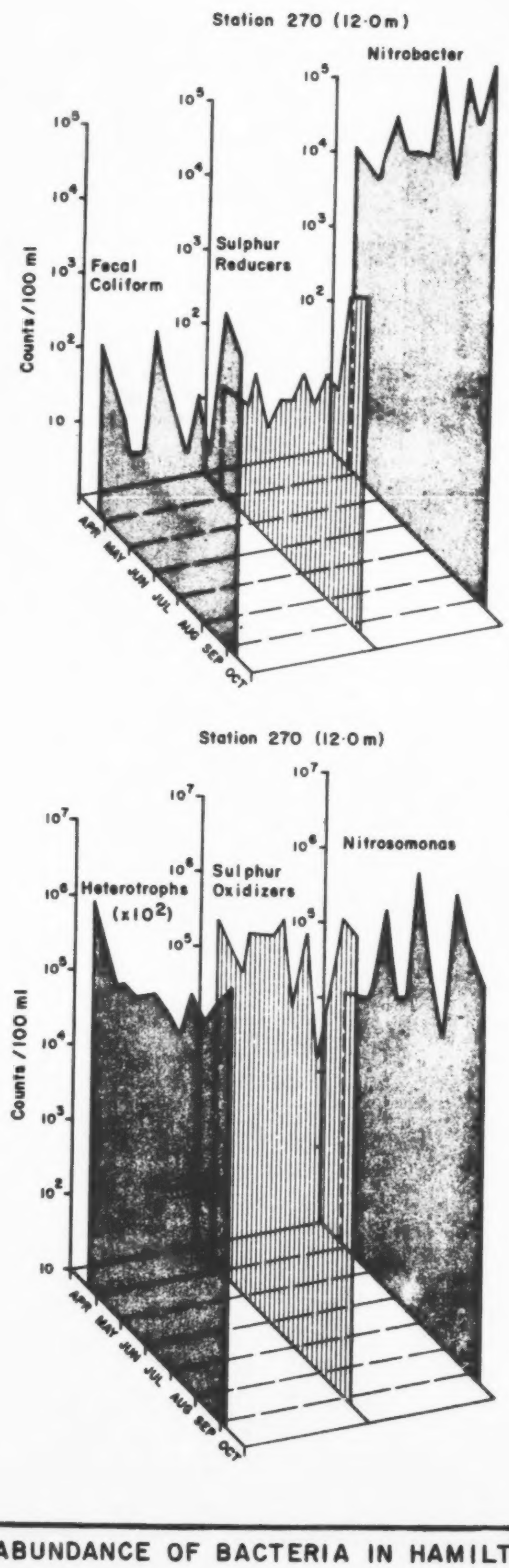

FIGURE 19 : TEMPORAL ABUNDANCE OF BACTERIA IN HAMILTON HARBOUR 1977.

HAMILTON HARBOUR STUDY

1977

Volume I

SECTION F

2-DIMENSIONAL NUMERICAL MODEL

SUMMARY

The two-dimensional depth-integrated numerical model of currents and water quality in Hamilton Harbour has been modified by including the real-time variation of currents and water quality at the major sources (the Ottawa St. slip and Hamilton STP) and the open boundary (exchange with Lake Ontario). This means that short-time variations of currents and water quality measured at these locations by recording current and water chemistry meters have been read directly into the model. Use of these data at intervals of minutes allows prediction of the effects on the harbour of large but short-term changes of water quality such as those observed at the Burlington ship canal.

Following the procedures used in the recent Toronto Harbour modelling study, the model was calibrated to physical parameters such as wind stress and bottom roughness by comparing modelled output with currents and water quality measured at intervals of minutes at a fixed internal point not used as external data input. However, it was found that agreement of observed and modelled results was far from satisfactory. The location of the best fit was several grid squares south of the metered location and moreover varied in location with modelled time. In addition, the model is incapable of simulating short-term changes in current speed, direction or water quality. It was concluded that the major deficiency in this modelling effort is the use of a two-dimensional model to describe a three-dimensional (depth-stratified) case.

Despite these shortcomings, computerized maps of water quality do indicate the control of water quality by advection (direct transport of pollutants by the water masses). This is shown by the shapes of the model concentration contours in the southeastern portion of the harbour. The contour maps also show the importance of the Burlington STP and Grindstone Creek in affecting water quality near their outlets, and the time-varying zone of influence of exchange with Lake Ontario.

INTRODUCTION

As part of the original Hamilton Harbour study (MOE, 1974), a two-dimensional depth-integrated numerical model was developed which is capable of assessing changes in water quality resulting from changes in harbour geometry, water withdrawals, and waste discharges, for varying meteorological conditions. The model was run for a number of conditions representing altered harbour geometry and industrial loadings, destratification, increased harbour-lake exchange and varied meteorological conditions. The most effective methods of water quality enhancement were found to be artificial destratification and a 66% loading reduction of the major waste inputs.

For more precise water quality predictions to be made, however, the model must be capable of considering phenomena which occur at very short time intervals (order of minutes). The importance of such phenomena has been demonstrated for Hamilton Harbour, and more particularly, the Burlington Ship Canal, by the recording meter results (MOE, 1975; Palmer and Poulton, 1976). This indicates that changes in conductivity of several hundred umhos, or in dissolved oxygen of over 50% saturation, can occur in a matter of minutes. However, the earlier model runs allowed for only the time variation of the boundary currents in the ship canal; flow data for the industrial and municipal sources and all concentration data were entered only as average values. In the present study, real-time data obtained from the current and water chemistry meter survey in 1974 for the Windermere basin, Ottawa Street slip, and the Burlington ship canal, have all been used directly in the numerical model in an attempt to simulate better the rapid variations in conditions known to occur.

Considering that the harbour is stratified in the summer months and the flow regime in the Burlington ship canal is complex with as many as three layers of different characteristics having been observed (MOE, 1975), a three-dimensional model is required for more complete prediction of harbour processes. Following the method used in Toronto Harbour (MOE, 1977), it is useful to operate the two-dimensional model in Hamilton Harbour and compare the results with the available real-time continuously recorded field data.

The version of the numerical model used in this study is identical to that used previously in Hamilton Harbour with the addition of real-time source and boundary inputs. The model has been described previously (MOE, 1974, 1977) and this will not be repeated.

INPUT DATA

Six pairs of recording current and water quality meters were operated in 1974. These installations occupied four distinct geographical locations (Figure 1). At the Burlington Ship Canal (locations M1 and M2), two Schneider robot monitors and two Plessey current meters were operated at depths representative of epilimnetic and hypolimnetic water. The offshore location (M6 and M7) comprised NERA self-contained water quality monitors as well as current meters (Plessey or Geodyne) also at epilimnetic and hypolimnetic depths. The other two locations each consisted of a single current meter and Plessey submersible water quality meter. The Ottawa Street slip installation (M5) was to monitor the combined effluents from this source, while the Windermere basin installation (M8) was to monitor the discharge from Red Hill Creek, including the Hamilton sewage treatment plant effluent. The offshore location (M6 and M7) was designed to provide an internal independent calibration point not used in the modelling runs. The details of the meter installations have been previously described (MOE, 1975).

The proper functioning of all the instruments would have provided an adequate data base for calibration of a three-dimensional model. In practice, as already emphasized (MOE, 1975; Palmer and Poulton, 1977), it is extremely difficult to maintain six sets of recording meters all operating simultaneously and in proper calibration. At no time were data available from the entire set of recording meters; in particular, chemistry meters M5 and M6 and current meter M7 failed to produce any useful data except for chemistry at M6 after July 11,1974. The data from current meters M5 and M8 were degraded by fouling of the rotors with suspended solids and algae; approximately 50% of the data record from current meter M8 indicated negligible speeds (less than 0.3 cm s^{-1}), and the remainder of the M8 results indicated slow currents which oscillated in either direction. For more details about meter operating periods, see MOE, 1975, Section D.

In addition to these shortcomings caused by operational problems, the data at M8 were unsuitable for direct input into the numerical model. As it was impossible to operate recording chemistry and current meters for any extended period of time next to the outfall of the Hamilton STP, interpolated mean daily flow results measured by the Hamilton STP were used with a time variation representative of the currents measured offshore of the outfall. Figure 2 shows the auto variance density spectra of the north component of M8 current averaged at half-hourly intervals. The longest significant periodicity is 2.6h; this periodicity was superimposed upon the daily flows with an amplitude sufficient to give a coefficient of variation of about 20%. This represents the variability of the Hamilton STP flow as observed in 1972 (MOE, 1974, Section E). A constant total dissolved solids (TDS) concentration of 560 mg L^{-1} was used. This represents a conductivity of 860 umho cm^{-1} which is an approximate average of measured results in Red Hill Creek, which receives the discharge of the Hamilton STP (Section I, Volume II).

With these limitations, the data available for modelling in real-time included the Burlington Ship Canal (currents and chemistry), the Ottawa Street slip (currents), and the synthesized real-time current data set for the Hamilton STP described above. Daily flow records for Grindstone Creek, a small source relative to the other sources, were interpolated to the model time interval. All other flows, and all concentrations except at the Burlington Ship Canal were entered as averages. Except for the Burlington STP, these constant discharges are small in volume compared to the major discharges and lake exchange which were metered. The input flows and concentrations used are summarized in Table 1.

Two additional corrections in the flow data were required. First, at location M5, due to the fouling of the rotor as already mentioned, a gradual decrease in meter response occurred. It was assumed that 10 days were required for the response to drop 50% and an exponential correction factor was applied. Second, due to the multi-layered flow regime in the Burlington Ship Canal as described previously (MOE, 1975, Section D), the current meter data set failed to describe completely the time variation of currents in the canal. In order to prevent apparent accumulation of water in the harbour during the model run, it was necessary to subtract 5 cm s^{-1} algebraically from the boundary current data.

These corrections provided a consistent input data set to the model for the period June 29-July 3, 1974. The real-time input data also included hourly wind data as recorded by the Hamilton Harbour police at a location near their dock. The input wind record is shown in Figure 3.

SELECTION OF MODEL PARAMETERS

As a component of the numerical model study in Toronto Harbour, which used real-time data inputs at intervals of minutes, a thorough investigation of model parameters was performed (MOE, 1977). This involved the checking of the hydrodynamic and mass balance time step length, effect of wind stress on a moving surface, and the bottom roughness coefficient (Manning's n), together with its interaction with water depth.

The hydrodynamic time step criterion as suggested by Williams and Hinwood (1976) and applied to Toronto Harbour was used for the 1974 Hamilton Harbour model run. The time step length Δt is expressed as a function of the space step Δx, as follows:

$$1 \leq \frac{\Delta t}{\Delta x}\sqrt{gh} \leq 2.5 \qquad (1)$$

where: Δx = space step length
g = acceleration due to gravity
h = maximum depth

An adequate time step length is obtained when further decreases in time step length produce no changes in calculated velocities or water levels, e.g. results are independent of time and space scales used.

Using this formula, and experience gained from modelling in Toronto Harbour (MOE, 1977), the required time step length for Hamilton Harbour would be of the order of 10 s using the previously employed space step size of 152.4 m. As this would require excessive amounts of computation time, a new model grid was set up with a space step size of 240 m (see Figure 4). Tests with this grid indicated stability was achieved with Δt=15 s. Following the methods used in Toronto Harbour (MOE, 1977), the time step length for mass balance calculations was set to five times this value, or 75 s.

The other physical parameters affecting model results are the wind stress and bottom roughness (Manning's n) coefficients. In common with the previous modelling in Toronto and Hamilton Harbours, the wind stress coefficient was set at 0.0032. However, the bottom roughness coefficient is not easy to define. Bottom friction is ordinarily determined in the field by comparing a measured velocity profile to a calculated profile based upon assumed wind stress and bottom friction. Although some velocity profiles were measured in Hamilton Harbour during 1976, the data were too variable to permit any meaningful calculation of Manning's n.

For the Toronto Harbour modelling study, a literature review of typical bottom friction coefficients was conducted, and a grid using 4 values of Manning's n was established on the basis that shallow waters tend to have higher n values than deeper or dredged areas. Accordingly, a similar grid was established for Hamilton Harbour (Figure 5). Several sets of n values were tested for 12 hours by comparing the fit of modelled data to observed data, and it was found that the values used in Toronto Harbour (n=0.040 to 0.060) were much too high to reproduce the observed currents at location M6. Test results suggested use of the values n_1=0.020, n_2=0.025, n_3=0.030 and n_4=0.040, and these were employed for a model run of longer duration, to be followed by comparison of modelled currents with observed currents and further refinement of the n values if necessary.

MODEL RESULTS

With the factors affecting model performance as discussed above, a numerical model run for 48 hours was performed, using input data for the period June 29, 1974 at 12.00 h to July 1, 1974 at 12.00 h. After evaluation of the modelled results as discussed below and further alteration of Manning's n values, the modelling was extended to 96 hours (input data until July 3, 1974). Pertinent input parameters used are summarized as follows:

1. Source and sink flow data according to text discussion and Table 1.
2. Average wind field according to Figure 3.
3. Wind stress coefficient = 0.032.
4. Manning's n values as follows: n_1=0.020, n_2=0.025, n_3=0.030, and n_4=0.040 used on grid shown in Figure 5.
5. Hydrodynamic time step = 15 s.
6. Mass balance time step = 75 s.
7. Minimum harbour water depth = 1.5 m.
8. Mass balance dispersion coefficient = 1.7 m^2s^{-1}.

The important fact of the volume of input data used in the real time modelling cannot be overemphasized. A model period of 48 to 96 h is long compared to the longest periodicities of significant magnitude, which are 12 h (lunar semi-diurnal tide) and 5 h (Lake Ontario uninodal seiche)(MOE, 1975, Section D). Such a model period therefore represents a reasonable test for the model. This 96 h of model run utilizes the following inputs: 96 wind vector readings, 576 current meter readings at each of four different locations and 288 water chemistry readings at each of 2 different locations. The validation test utilizes an additional 576 current meter readings and 192 water chemistry readings at one location.

Modelling was also performed with Mannings n_1 = 0.016, n_2 = 0.023, n_3 = 0.030, n_4 = 0.040, and n_1 = 0.025, n_2 = 0.030, n_3 = 0.035, n_4 = 0.045. For the sake of simplicity, only the n_1 values will be referred to in the following discussion; but reference to a particular n_1 value implies use of the related n_2, n_3 and n_4 values of that particular group.

COMPARISON OF OBSERVED AND MODELLED VELOCITIES

Observed and modelled velocities were compared by converting the calculated U and V components into a resultant speed and compass direction, and plotting these together with the observed currents as a function of time for location M6. Different model grid locations were used in the vicinity of the current meter in testing the modelled and observed results. As will be seen, the location of best fit varied somewhat with Manning's n and even with time at constant n. The locations used for comparison are shown in Figure 6.

Although the modelling was first performed for 48 h and later extended to 96 h, it is convenient to present data for the entire modelled period together. Comparisons of observed and modelled velocities are given in Figure 7 for location (14, 8) and n_1 = 0.016; Figure 8 for location (14, 8) and n_1 = 0.020; Figure 9 for location (14, 7) and n_1 = 0.020; and Figure 10 for location (14, 6) and n_1 = 0.025. These locations represent the best fit to observed data obtained under the conditions used in each run, after summing the differences between observed and modelled velocities for several runs and columns near the validation point.

The initial effort (n_1 = 0.020; Figure 8a) showed an underestimation of speeds for the first 24 h. During the second 24 h, rapid changes in the observed direction were not simulated at all. In an attempt to improve this situation, modelling at n_1 = 0.016 was attempted. The result (Figure 7a) shows a much closer agreement to observed currents for the first 32 h. The model approximates the observed, rapid direction changes between 37 and 40 h, but does not simulate the remainder of the compass oscillations in the 32 to 48 h period.

In both instances, short period time variations of measured currents (order of a few hours or less) were not simulated at all. This was true for all modelled periods, and is also emphasized by the model autospectra presented later.

As the overall result for the first 48 h was somewhat better with n_1 = 0.016, this value was used initially for modelling the next 48 h. The result (Figure 7b) showed a rough simulation of observed speeds, but contained two sudden shifts in modelled direction which were not observed (the observed current direction was almost constant from southeast to south for most of this time period, shifting drastically only in the last 4 h). Consequently the modelled current was at times almost opposite in direction to the observed.

At this stage, the run with n_1 = 0.020 was extended to 83 h. The comparison at the same grid point (14, 8; Figure 8b) showed generally poor agreement, with a shift in modelled current direction to opposite the observed direction being found at about 72 h. For the same model run, however, the adjacent grid point (14, 7) showed a much better fit to the observed data between 50 and 72 h modelled time (Figure 9b); however, this grid point was unacceptable during the first 48 h (Figure 9a). These two sets of results (Figures 8 and 9), derived from the same model run (n_1 = 0.020), showed that there are problems in the fit with observed data both with time and location.

In an attempt to improve the output for direction during the last 48 h, the model was rerun for this period at n_1 = 0.025, starting from the result at 48 h for n_1 = 0.020. The best fit between observed and modelled results is showed in Figure 10. A good agreement between observed and modelled directions is evident for most of the modelled time, but speeds are too low for portions of the record, with the observed time variations of the speeds not being simulated. It is probable that this value of Manning's n would not have simulated the observed variations in current direction between 32 and 48 h, had the simulations included this time interval.

In general it is observed that the 2-dimensional model in its present form allows a qualitative simulation of currents as measured at location M6, but lacks the capability of modelling rapid changes in speed or direction. It was necessary to use modelled data from a location several grid points away from the actual meter location to achieve this limited degree of fit, and the grid location of best fit tended to shift from one point to an adjacent point as a function of modelled time. Use of the U component from 1 square and the V component from the next square (but still adjacent on the space - staggered grid) did not give any improvement. The result of that test is not detailed here.

MODEL PREDICTIONS OF HARBOUR-WIDE CIRCULATION

Predicted currents are shown in Figure 11 after 54 hours of modelled time with $n_1 = 0.020$. This time immediately followed an interval of high winds, with the average wind speed for the previous hours being 7.5 m s^{-1} and the maximum hourly wind speed being 8.5 m s^{-1}, consistently from the west. The strongest currents (up to 30 cm s^{-1}) flow with the wind in an eastward direction parallel to the north shore, following the shore in shallow water around to the vicinity of the Burlington Ship Canal. South of the Canal, in the vicinity of the validation point, M6, the current regime is somewhat confused. A weaker flow with the wind is also evident next to the western part of the industrial shore, the slower speeds being related to the larger water depth in this area. In the deep central part of the harbour, an average return current is predicted, with the strongest return current being adjacent to the north shore current. The presence of a coastal jet along the north shore is in qualitative agreement with other modelling studies (e.g. Simons, 1971), who showed a nearshore jet flowing with the wind in Lake Ontario, and a central return flow in the deeper waters.

As the wind regime during the modelled period (Figure 3) was largely unidirectional, the overall features of the current pattern are similar at all modelled times. Consequently no additional plots of harbour-wide currents are presented.

MODEL PREDICTIONS OF WATER QUALITY DISTRIBUTION

As in the previous models of Toronto and Hamilton Harbours (MOE, 1974, 1977), water quality distribution was approximated by total dissolved solids (TDS), as measured by conductivity. This was used as it is largely conservative (non-reacting), and real-time data were available at 20-minute intervals for two depths in the Burlington Ship Canal. Although changes in concentration due to chemical and biological reactions are not simulated, the use of TDS does represent a reasonable approximation to the spatial distribution of water quality as created by advection and dispersion.

Due to the large spatial gradient of observed conductivity in the southeastern part of the harbour close to the major discharges, it was decided to start the model with higher TDS concentrations in these areas. Results of a conductivity transect done June 14, 1977, between Windermere basin and a point west of the mouth of the Ottawa Street Slip were converted to total dissolved solids and entered into the model grid. This produced an initial total dissolved solids contour plot given in Figure 12. Although lake-harbour exchange and the other sources (Table 1) do exert a significant effect on the harbour TDS, no allowance was made for these sources on the initial TDS distribution.

Computerized plotting representations of TDS contours predicted by the model are presented in Figures 13-16 for 24, 48, 60 and 96 h modelled time. These figures represent typical water quality distributions obtained; in general other time intervals did not produce greatly different results and are not reproduced here.

The effects of the major discharges and their variations in real time on harbour water quality in the southeast portion of the harbour are evident in the figures. The control of water quality by advection is apparent when these figures are compared to the modelled currents. For example, for much of the modelled time, the water in the southeastern portion of the harbour (near station 20; model grid rows 6 to 12) tends to flow towards the southeast close to the Burlington beach strip (model column 6) and to the northwest closer to the industrial shore (model column 7) (see Figure 11). This flow pattern produces the typical shape of the 325 and 340 mg L^{-1} contours in Figures 14 and 15. As flow is weaker nearest the Windermere basin, the position of the 380 mg L^{-1} contour is almost constant.

The effect of lake-harbour exchange and of the other sources can be followed from the figures. The only other sources of sufficient magnitude to be observed are the Burlington STP and Grindstone Creek, which affect small areas in the northeast corner and far west end of the harbour, respectively. Although the model results do show increased TDS values near Randles Reef, the spatial extent of the increase was insufficient to appear on the present maps. Near the Burlington STP and Grindstone Creek, TDS concentrations are above 340 mg/L after 96 h modelled time. The extent of influence of the Burlington STP is observed to include station 252 (one of the four major water chemistry and biology stations). Therefore, it is reasonable that effluent discharged by the Burlington STP will affect the results of the sampling program at this station and any unusual discharge from the STP should be observed within four days of discharge. As this source was programmed into the model as a constant, no inference about real-time variation of the plume area can be drawn from the results.

The most interesting observed result in the figures is the variation of the area affected by lake-harbour exchange as depicted by the 310 mg L^{-1} contour. This contour varies in location from within the canal (Figures 13 and 15) to an area encompassing roughly 0.4 km^2 around the harbour end of the canal, including station 269 (figures 1 and 16). The zone of influence of lake-harbour exchange varies rapidly with time between these extremes due to the rapid reversals of water flow within the canal, as already well documented (MOE, 1975; Palmer and Poulton, 1976; Kohli, 1979). Station 269 is included within the 310 mg L^{-1} contour roughly 10% of the time. Profiling studies at this station indicate the existence of water of largely Lake Ontario composition (conductivity below 400 umho cm^{-1}) within the hypolimnion most of the time but rarely, if ever, in the entire water column. Sediment studies (MOE, 1977b, 1978) indicate that this area is affected by lake-harbour exchange, but that an area slightly to the west (station 22) is not much affected by exchange.

The results of the present model runs certainly indicate a zone of lake-harbour exchange effects within qualitative agreement with observed data. However, it should be expected that the three-dimensional model will define this zone far better, including an estimate of the proportion of time that the hypolimnion of station 269 is occupied by lake water, as well as the spatial and temporal variation of parameters such as dissolved oxygen.

In Figure 17, a comparison of modelled conductivity (total dissolved solids x 1.54) with observed conductivity at location M7 is presented. Large variations in the first 36 h of modelled time are not simulated at all; during the next 36 h there is closer agreement but the oscillations in the two time series do not coincide. Although this result was obtained with Manning's $n_1 = 0.020$, the result with Manning's $n_1 = 0.016$ was similar. A possible reason for the inability to simulate the observed time variation of conductivity is the observed variation of this parameter with depth, as seen in most of the water chemistry profiles at station 4 during the summer period. Figure 18 shows a depth profile of conductivity as measured July 26, 1977. As this behavior is typical during summer stratification, accurate simulation cannot likely be obtained using a 2-dimensional model.

TIME SERIES ANALYSIS OF MODEL PERIODICITIES AND CROSS CORRELATION WITH OBSERVED DATA

A set of model U and V velocity and concentration data at a 10 minute interval from row 14, column 8 of the model grid (near current meter location M6, Figure 1) was analyzed by standard time series techniques (Jenkins and Watts, 1968). The results are shown in Figures 19 to 21. Unlike the modelled results for Toronto Harbour (MOE, 1977), which displayed several highly significant periodicities of the order of minutes, more than 99% of the variance was found at near zero frequency. A minor peak appears in the V-velocity spectrum at 1.3 h (frequency of 0.75 h^{-1}), which is one-half the period of input flow data from the Hamilton STP discussed earlier. No apparent reason for this periodicity is evident.

Cross-correlation of the modelled data at several grid locations with observed currents and chemistry at locations M6 and M7 was attempted. The only significant coherence in some cases was the V component at 2.6 h (the input periodicity of Hamilton STP flow). Few or no other significant coherences were obtained. These results, as well as the model-meter comparison presented earlier (Figures 7-10 and 17) emphasize the present inability of the model to simulate events occurring over short periods despite the use of real-time data for the canal and major discharges over intervals of minutes.

DISCUSSION

The comparisons between observed and modelled results as presented indicate that the present model is able to simulate the harbour currents and water quality on a qualitative basis, but that very little short-term variations were obtained. Despite the fact that currents were entered at 10 minute intervals for the major sources and open boundary, and chemistry values were entered at 20 minute intervals on the open boundary, the only significant cross-correlation between the model and independent current meter data was for the 2.6 h periodicity which was superimposed upon the input flows from the Hamilton STP.

To obtain even a qualitative agreement with observed currents (Figures 7 - 10), it was necessary to select model grid points (Figure 6) which were somewhat closer to the industrial shoreline in the vicinity of the Ottawa Street slip. In addition, the location of the grid point with the best fit changed somewhat with time over the 96 h modelled period. Figure 11 shows that there is considerable local variation of currents in this part of the harbour, with the strongest currents near the eastern shore (beach strip) in a northwest to southeast direction, opposite to observed currents at meter location M6. These differences may be related to the actual spatial variations of water depth in this area, or more probably to the existence of thermal and chemical stratification. Three-dimensional model studies in the Great Lakes (for example, Simons, 1975) tend to show return currents against the wind in deep water areas, with frequent occurrences of current shear patterns (surface water transport with the wind and bottom water transport against the wind). The variations in fit between modelled and observed values at different times for separate grid points may be related to the use of a two-dimensional model in a stratified situation, and possibly to the limits on spatial resolution imposed by the present model grid.

The validity of the present modelling effort is also highly dependent upon the values of input physical parameters such as surface and bottom stress, as already mentioned. Selection of these parameters is a difficult and expensive task as it involves repeated runs of the model with small variations in the parameters, followed by comparison of observed and modelled data for various grid points. In his independent work on numerical modelling of Hamilton Harbour using the same input data as used here, Rasmussen (1978) used two statistical methods to evaluate model fit. These were: (a) least-squares comparison between modelled and observed currents; (b) "minimax criterion", or minimizing the maximum model error (absolute value of difference between modelled and observed current). Using these criteria for 12 hours of modelled time, he obtained the best fit to observed currents with a wind-stress coefficient of 0.0032 and Manning's n_1=0.0126 to 0.0130 (as in the present study, a grid of higher n values was used in rougher, shallower areas). His wind-stress coefficient is the same as used here but the Manning's n is lower (corresponding to higher currents and more rapid changes in direction).

During storm periods as presently modelled, the effect of wind stress is important during periods of strong wind whereas the bottom stress controls the rate of current decay after the event (Simons, 1973). Additionally, bottom stress can be specified in terms of several different formulations (Cheng, Powell and Dillon, 1976); indeed, the formulation used has a bearing on the grid dispersion or smoothness parameter (local variation of the water level). Although more complicated in computational effort, the non-linear formulation used in the present Hamilton Harbour model emphasizes the depth dependence on bottom roughness with strong frictional effects for high currents and shallow depths.

Spatial and temporal variations of surface stress, which were not invoked in the present study, could also be included. Donelan (1978) suggests that wind drag is highly dependent upon wave fields and thus upon fetch. Therefore, the wind stress coefficient should be a function of location and wind direction, increasing as the upwind distance from a grid point to the upwind shore increases.

A significant physical parameter which is involved in the water quality model is dispersion. This includes the effect of sub-grid scale turbulence on both currents and water quality. Leendertse and Liu (1977) have suggested that vertical and horizontal turbulent exchanges play an important role in determining sub-grid scale dispersion, and they introduce modifications to their three-dimensional model to account for these effects. The vertical exchange is related to turbulent effects caused by flow moving over the bottom, air moving over water, and velocity gradients in the vertical direction. Horizontal exchanges are caused by large two-dimensional horizontal eddies. Non-linear horizontal eddy viscosity coefficients are introduced to accomplish the dissipation of vorticity which cascades from larger scales to smaller scales as a result of the two-dimensional horizontal turbulence. This coefficient is a function of the local velocity deformation calculated in the finite difference grid. It is possible that neglect of these turbulent exchanges in the present model could account at least partly for the failure of the model to simulate short-term exchanges observed at the validation location.

Despite these limitations, the dispersion coefficient presently used does exert a smoothing effect on concentration contours and helps to counteract numerical instability effects (concentration waves) produced by the finite difference approximations near sources of high concentrations. This effect of dispersion was verified by performing a model run with the dispersion coefficient reduced by a factor of 10. The resulting output contained significant concentration waves in the area closest to the largest waste discharges.

The basic shortcoming in the present modelling effort, and probably the fundamental reason for the limited success in simulating observed currents and water quality, is the use of a two-dimensional model to describe a three-dimensional problem. As already pointed out, other studies have shown a considerable effect of water depth and thermal stratification on water movements, and hence, water quality. Therefore, further effort be directed to the three-dimensional model, thus allowing for appropriate simulation of the stratified case. In addition, dissolved oxygen concentrations may be modelled, using input data from the monitors which provide dissolved oxygen values at 20 minute intervals. This would include the effect of sediment and water column oxygen demand, as measured in the last few years (Section D; MOE, 1978, Section D). Given proper input data, additional parameters could be included. Furthermore, the model could be extended to multiple grid sizes, thus allowing a finer grid to be used in the southeastern part of the harbour (for example, Wickramartne et al, 1976). This would allow simulation of water quality gradients in better detail at minimum increased computer costs and provide for testing the effect of proposed construction projects such as landfilling along the beach strip, and alternatives for management of Windermere Basin.

Although it has been shown that the 2-dimensional model fails to reproduce the detailed time-dependence of observed currents, the model is still useful for approximate predictions of water quality under non-stratified conditions. Concentration contours obtained using different meteorological conditions can be used to define the zones of greatest water quality impairment, as well as the extent of reduction upon reducing waste loads, and thus be useful in defining mixing zones or limited-use zones about waste outfalls as proposed by the Ontario Ministry of the Environment and the IJC. Furthermore, as recently done in Toronto Harbour (MOE, 1980), the model can be used to provide an estimate of the areas affected by stormwater runoffs in short time scales (minutes to hours) and the effect of diversion of such runoffs.

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TABLE 1

SOURCE AND SINK DATA USED FOR NUMERICAL MODEL HAMILTON HARBOUR, JUNE-JULY 1974

Map I.D.	Outfall or Intake	Flow ($m^3 s^{-1}$)	Conductivity (umho cm^{-1})
A	Hamilton WPCP	3.68*	860
		3.38	
		2.98	
		3.30	
		3.26	
B	Ottawa St. Slip**	metered	592
C	Stelco Intake !2	-14.9	-
D	Stelco S. Open Cut Sewer	2.72	677
E	Stelco N. Trunk Sewer	3.04	477
F	Stelco Intake !1	-2.40	-
G	Stelco !3 Open Hearth Sewer	2.40	569
H	Stelco 148" Plate Mill	0.94	555
I	Dofasco raw water intake	-8.9	-
J	Dofasco (coke oven by-products, boiler house discharge, silicon steel)	2.74	628
K	Skyway WPCP	6.83	738
L	Dundas WPCP	0.066	738
M	Grindstone Creek	0.64*	625
		0.57	
		0.49	
		0.40	
		0.34	

Note:

Negative flows are intakes (concentrations not required).

* Daily flows for 5-day period June 29-July 3, 1974 were interpolated. A variation of 20% was added to source A with a periodicity of 2.6 hr (longest observed periodicity at location M8).

** Includes: Stelco (E. side lagoon, HCl regenerator and cold mill, hot strip mill, heavy gauge shear line), Dofasco (lagoon, Ottawa St. sewer) and CIL (total plant less service water intake).

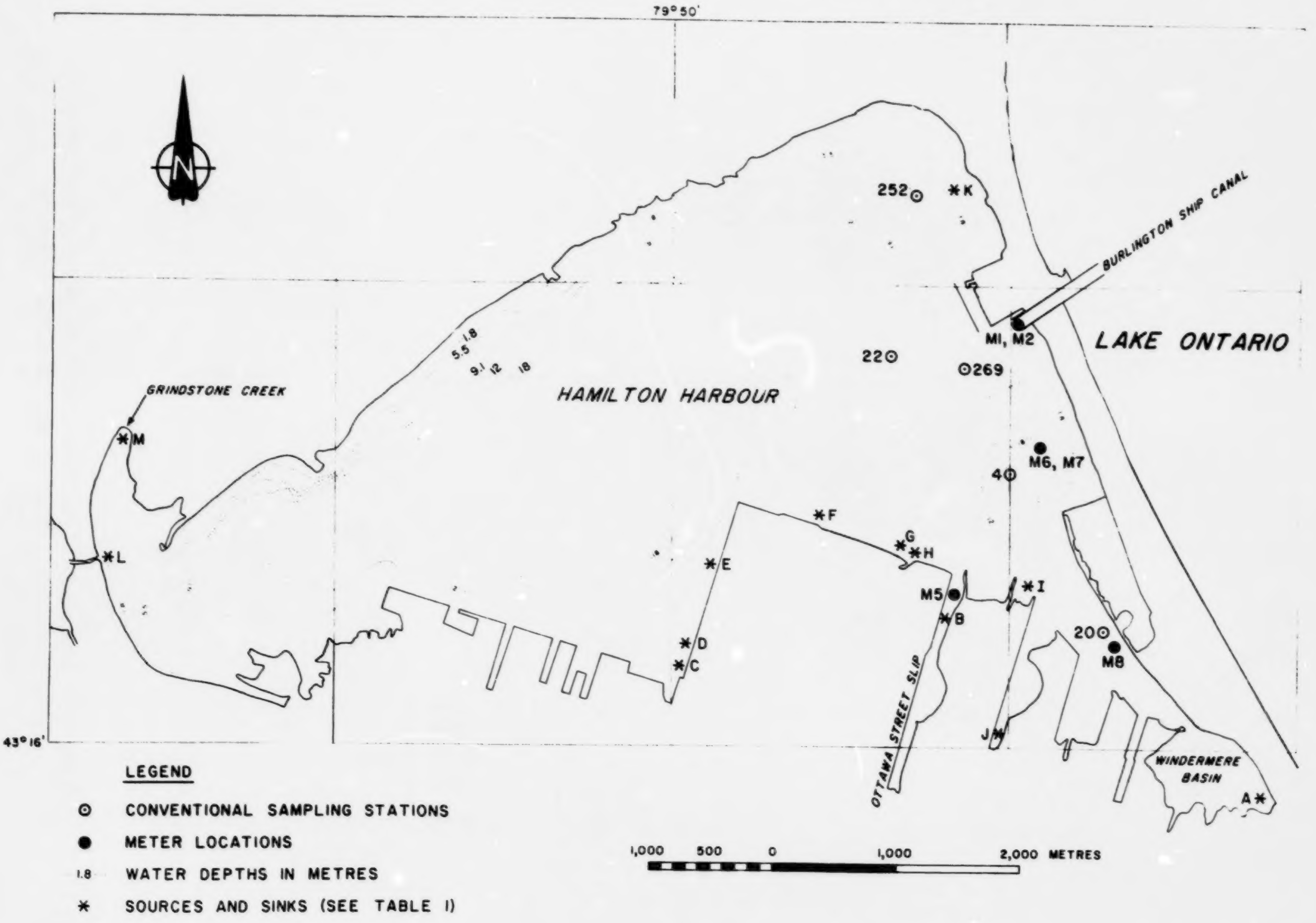

79° 50'
43° 16'
N
BURLINGTON SHIP CANAL
LAKE ONTARIO
HAMILTON HARBOUR
GRINDSTONE CREEK
WINDERMERE BASIN
OTTAWA STREET SLIP
252
22
269
4
20
M1, M2
M6, M7
M5
M8
A
B
C
D
E
F
G
H
I
J
K
L
M
1.8
5.5
9.1
12
18
LEGEND
CONVENTIONAL SAMPLING STATIONS
METER LOCATIONS
1.8 WATER DEPTHS IN METRES
SOURCES AND SINKS (SEE TABLE I)
1,000
500
0
1,000
2,000 METRES

FIGURE I - HAMILTON HARBOUR SAMPLING AND METER LOCATIONS.

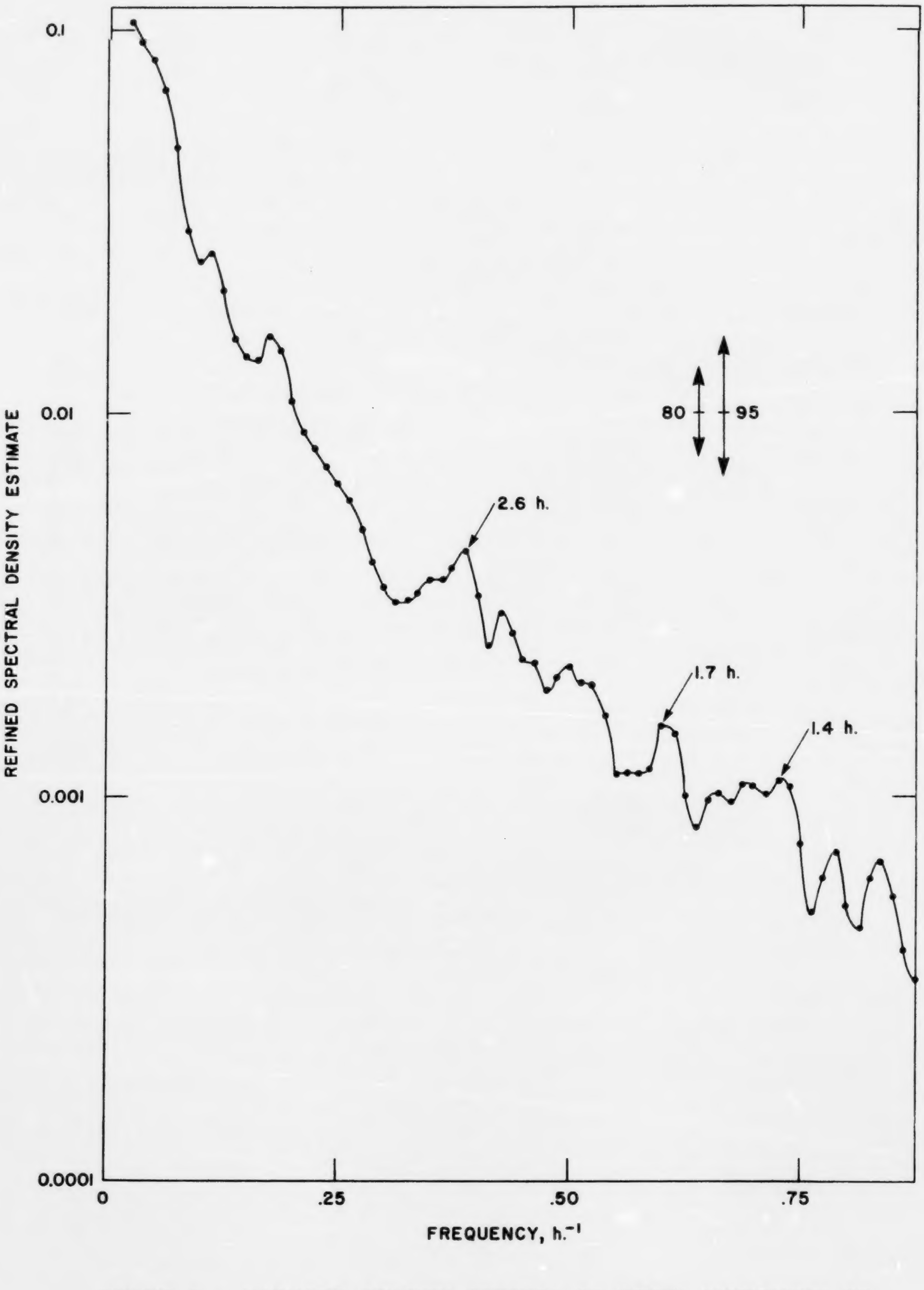


FIGURE 2 - VARIANCE DENSITY SPECTRA OF NORTH COMPONENT OF CURRENTS, LOCATION M8, HAMILTON HARBOUR JUNE-JULY, 1974.

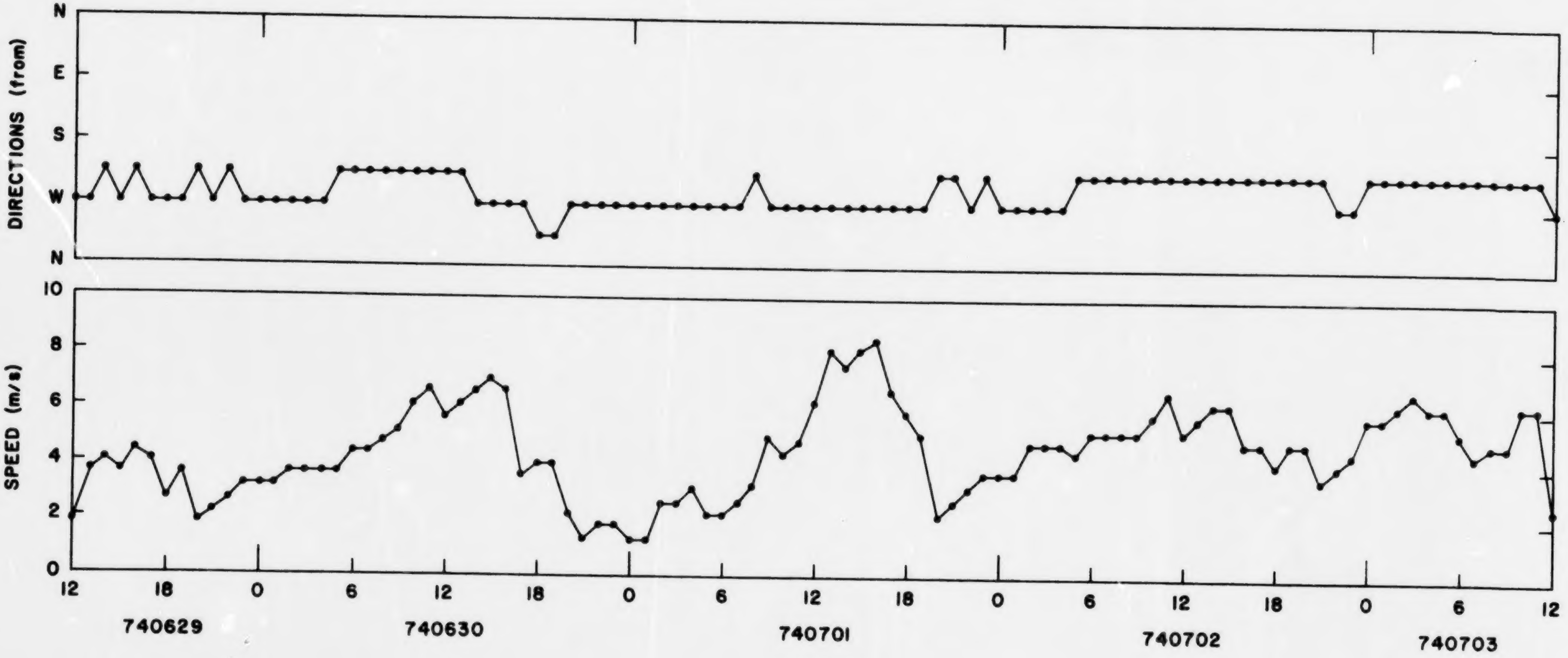


FIGURE 3 - WIND DATA INPUT TO NUMERICAL MODEL, AS RECORDED BY HAMILTON HARBOUR POLICE.

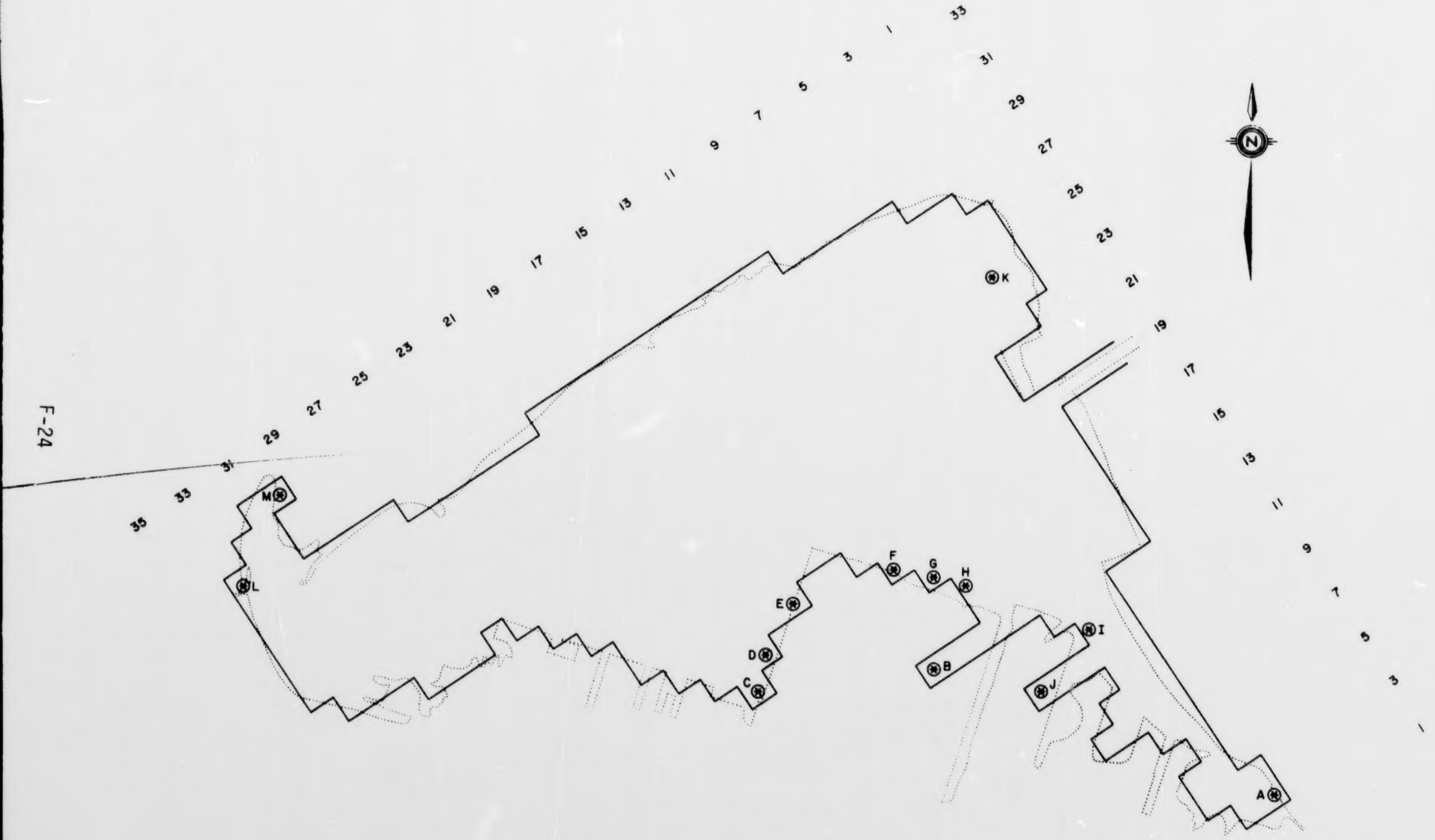
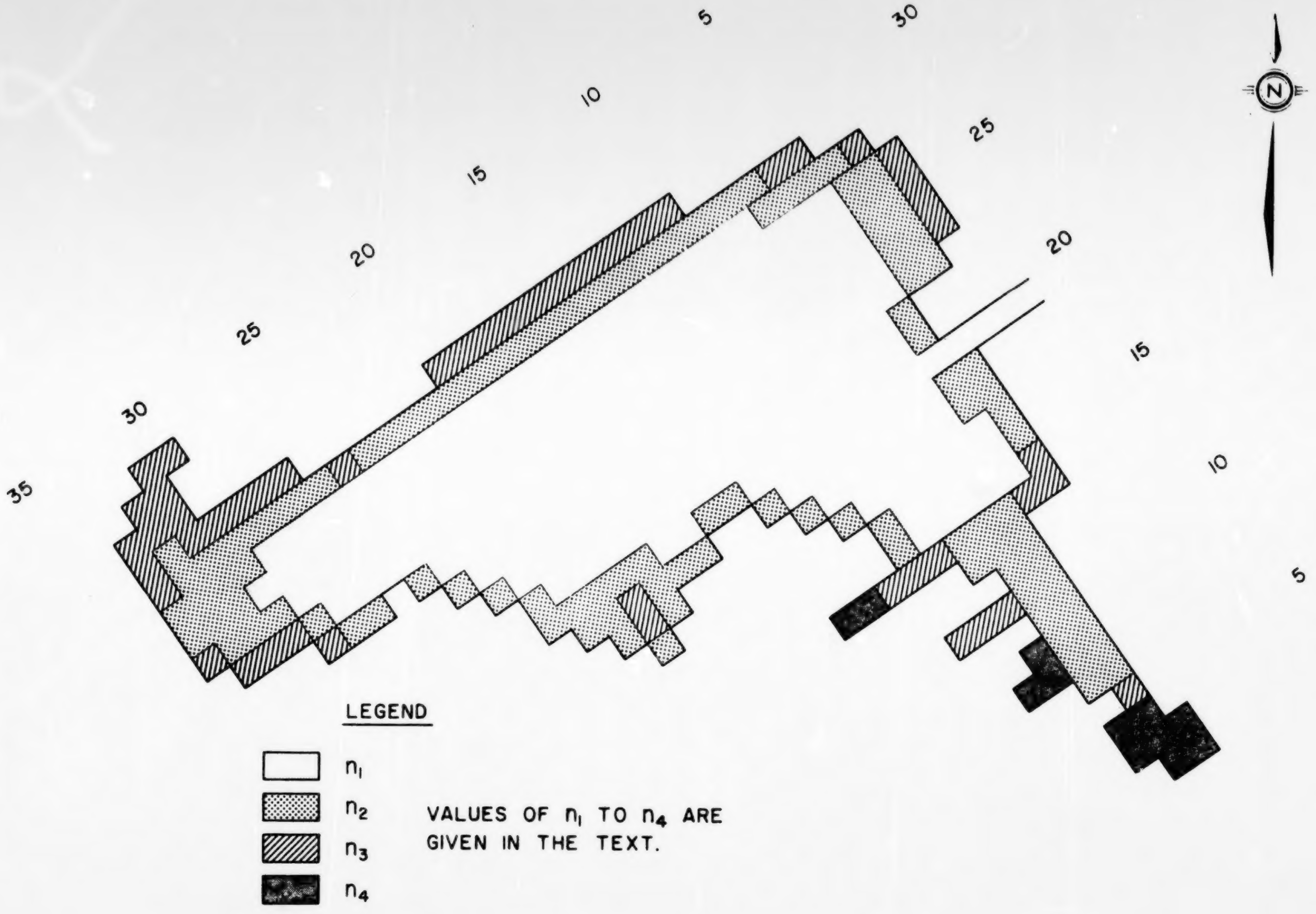

N
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
A
B
C
D
E
F
G
H
I
J
K
L
M

FIGURE 4 - HAMILTON HARBOUR NUMERICAL MODEL GRID.


5
30
10
25
15
20
20
25
15
30
10
35
5
LEGEND
n_1
n_2
n_3
n_4

VALUES OF n_1 TO n_4 ARE GIVEN IN THE TEXT.

FIGURE 5 - MANNING'S n VALUES USED IN HAMILTON HARBOUR MODEL.

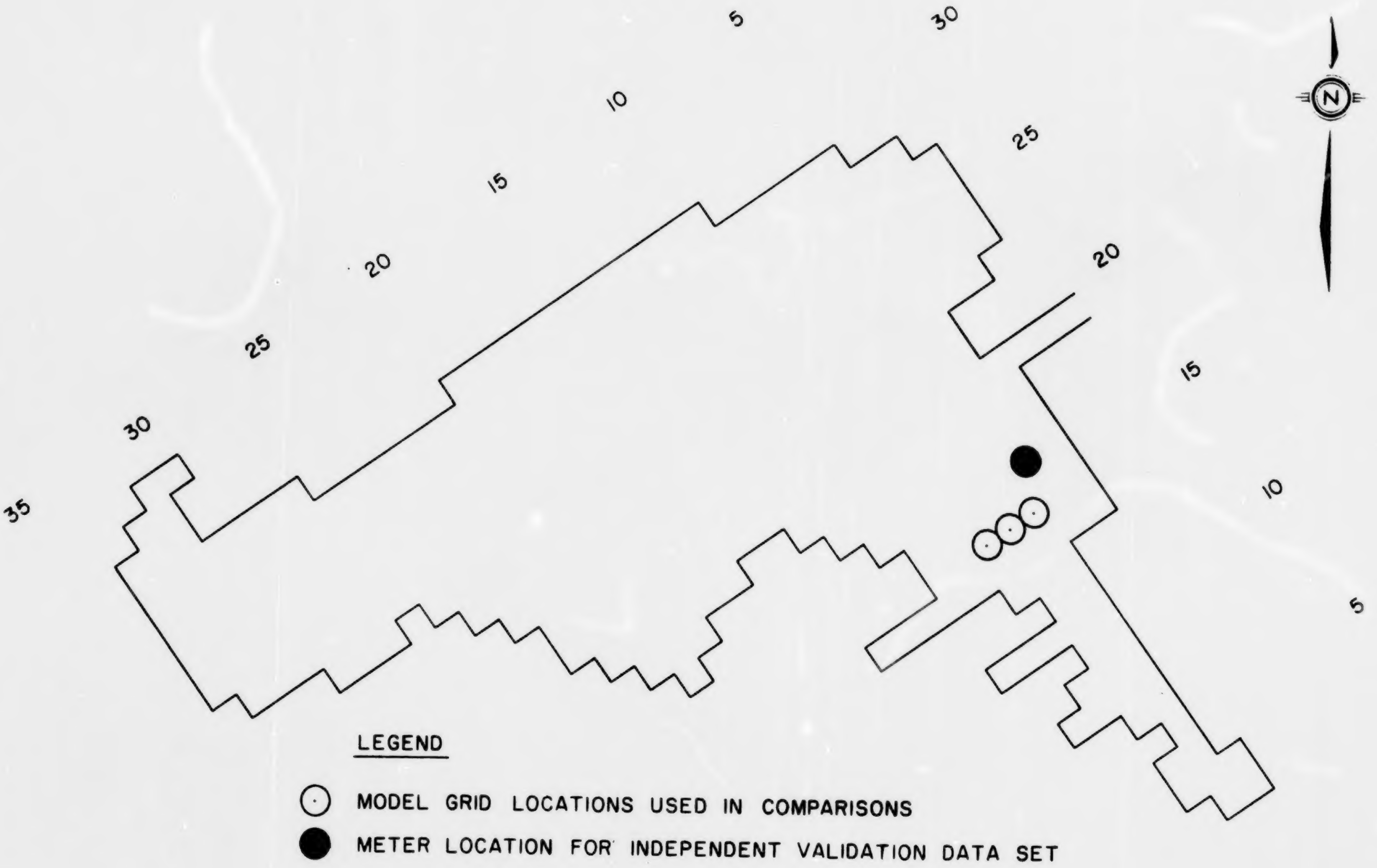

5
30
10
25
15
20
20
25
15
30
10
35
5
LEGEND
○ MODEL GRID LOCATIONS USED IN COMPARISONS
● METER LOCATION FOR INDEPENDENT VALIDATION DATA SET

FIGURE 6 - LOCATIONS OF MODEL GRID POINTS USED FOR MODEL VALIDATION AGAINST INDEPENDENT METER POINT.

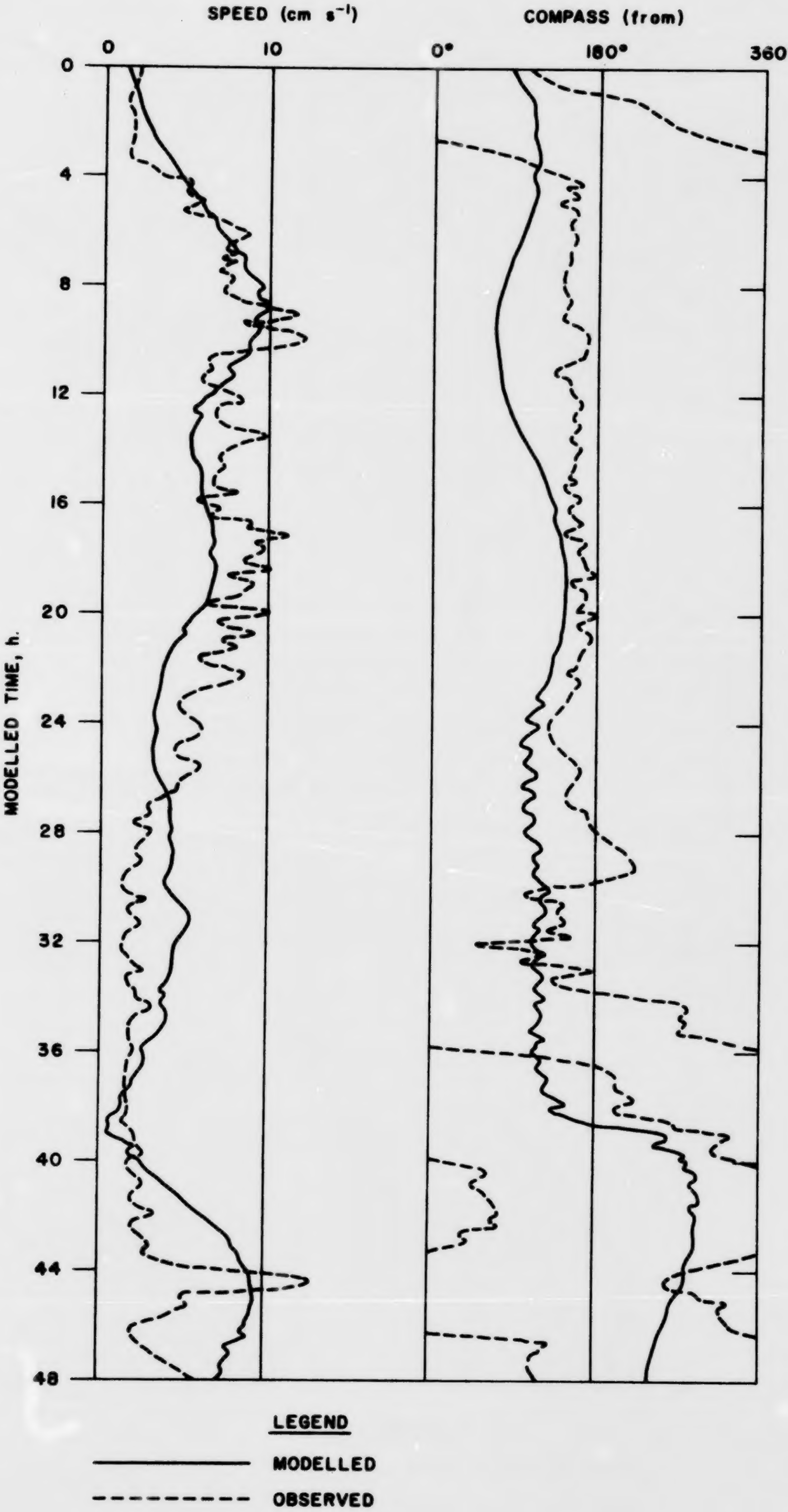


FIGURE 7a - COMPARISON OF OBSERVED AND MODELLED VELOCITIES FOR LOCATION (14,8) AND MANNING'S N = .016,.023,.030,.040, STARTING AT 1200 h. ON 740629.

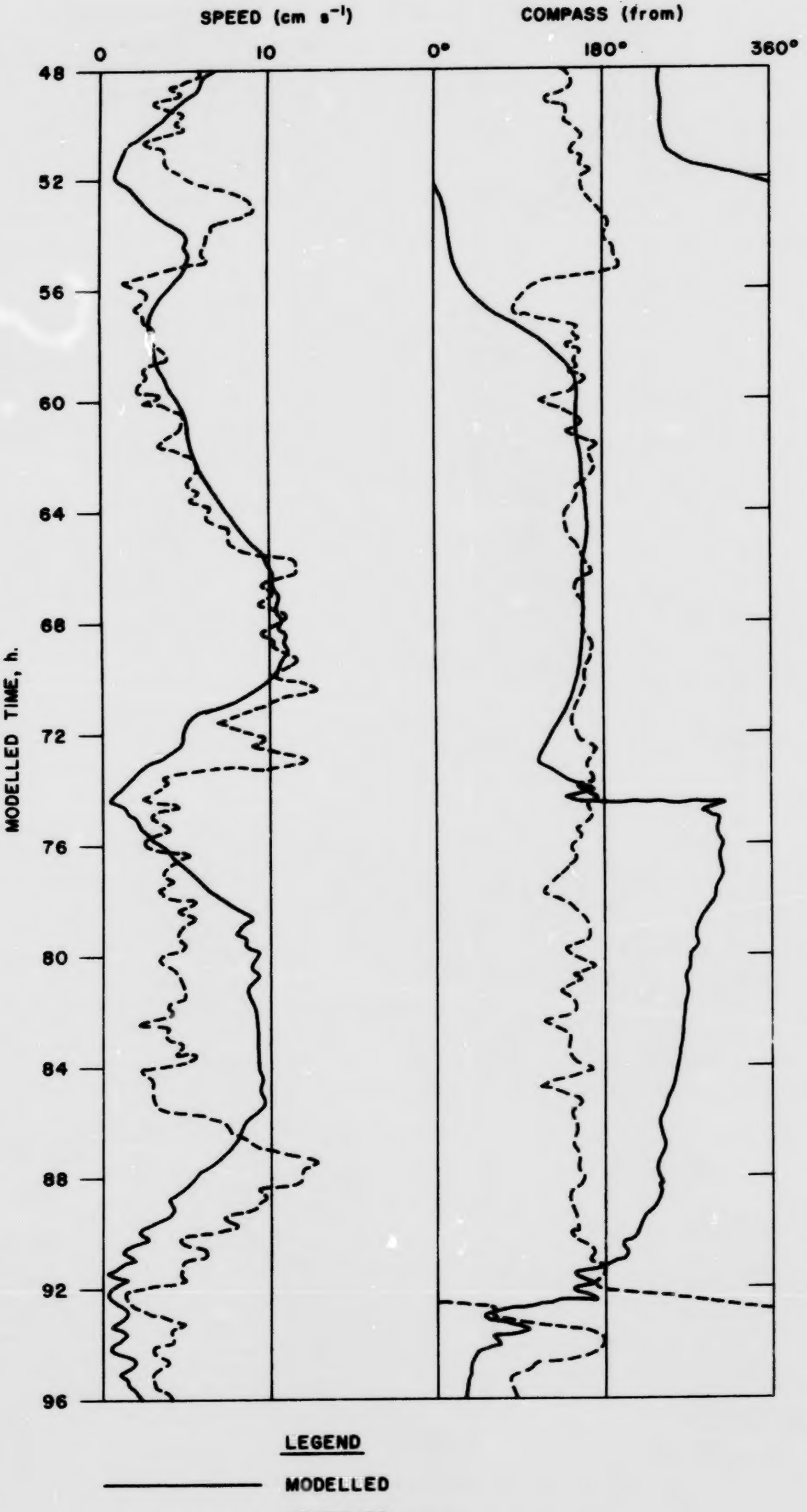


FIGURE 7b - COMPARISON OF OBSERVED AND MODELLED VELOCITIES FOR LOCATION (14,8) AND MANNING'S N = .016,.023,.030,.040, STARTING AT 1200 h. ON 740701.

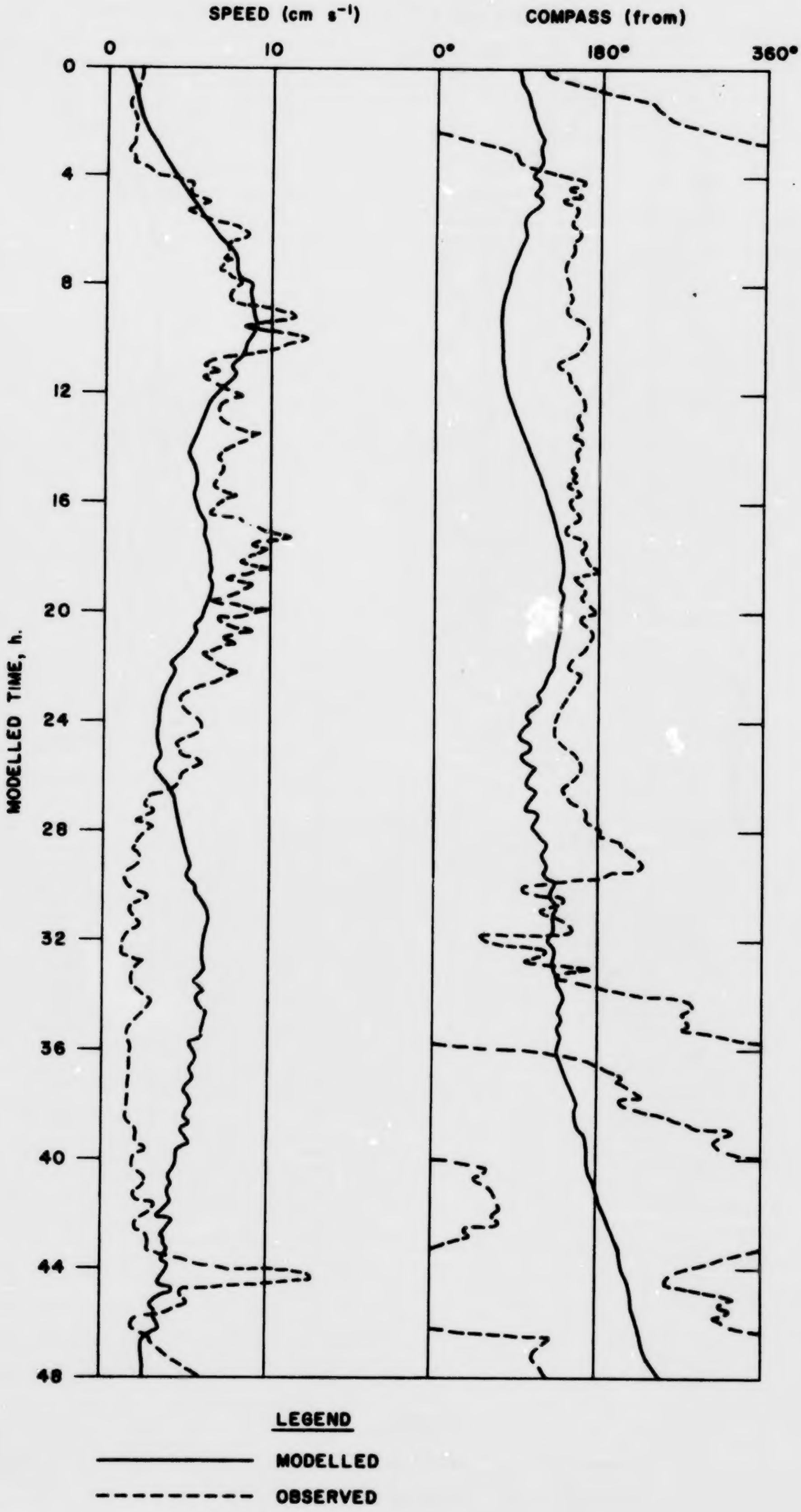
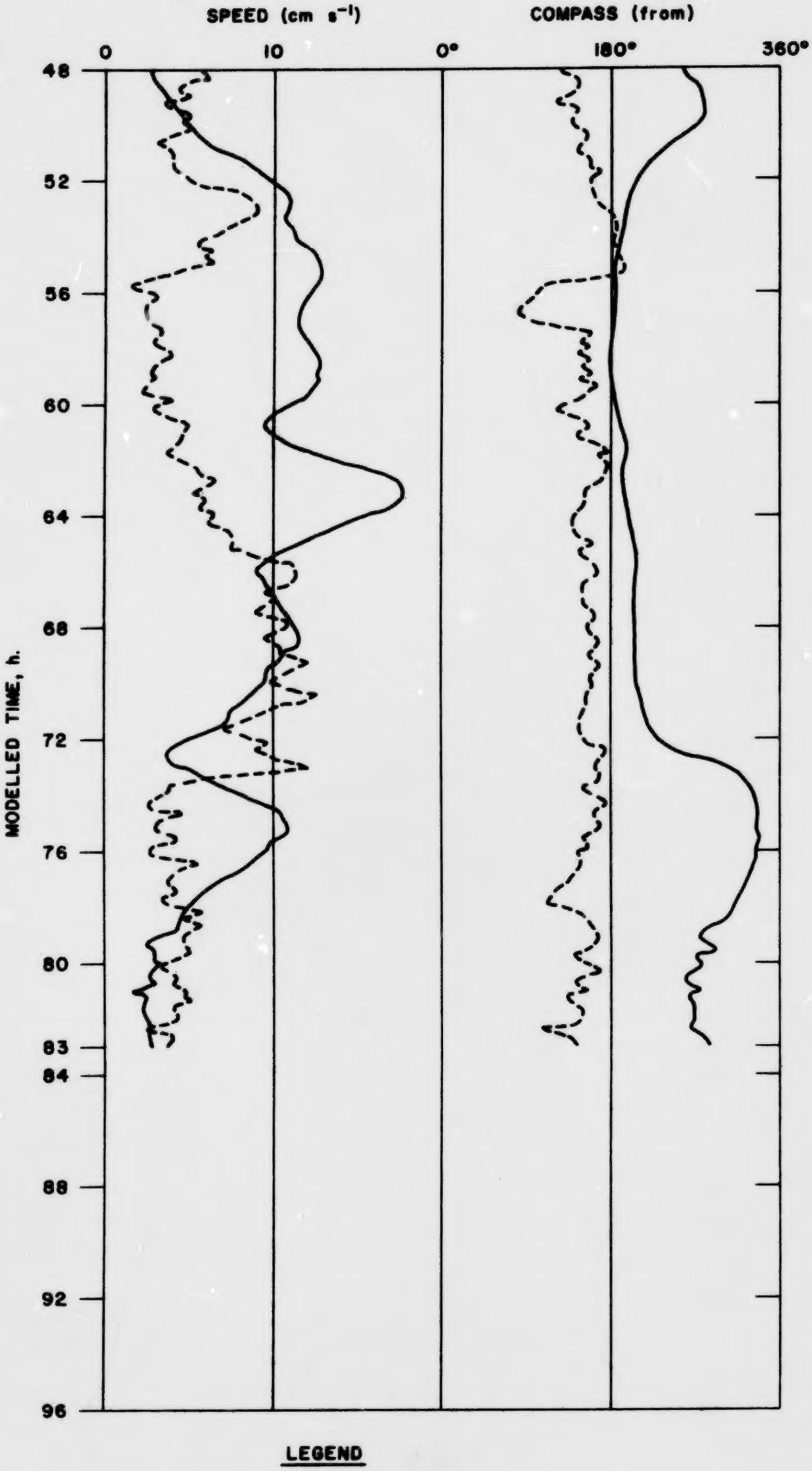


FIGURE 8a - COMPARISON OF OBSERVED AND MODELLED VELOCITIES FOR LOCATION (14,8) AND MANNING'S N = .020, .025, .030, .040, STARTING AT 1200 h. ON 740629.



LEGEND

——— MODELLED

- - - - - - - - OBSERVED

FIGURE 8b - COMPARISON OF OBSERVED AND MODELLED VELOCITIES FOR LOCATION (14,8) AND MANNING'S N = .020, .025, .030, .040, STARTING AT 1200 h. ON 740701.

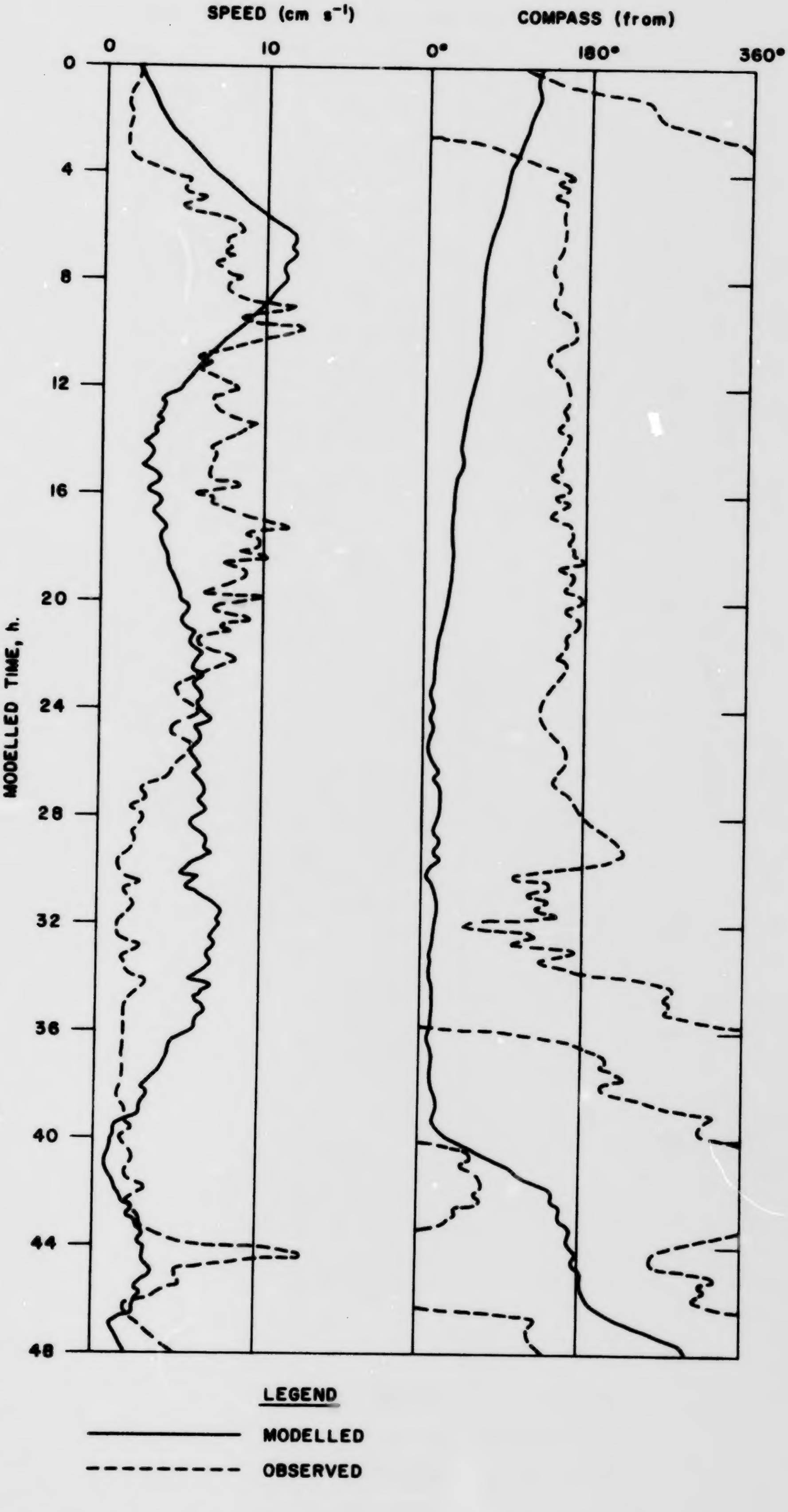


FIGURE 9a - COMPARISON OF OBSERVED AND MODELLED VELOCITIES FOR LOCATION (14,7) AND MANNING'S N = .020, .025, .030, .040, STARTING AT 1200 h. ON 740629.

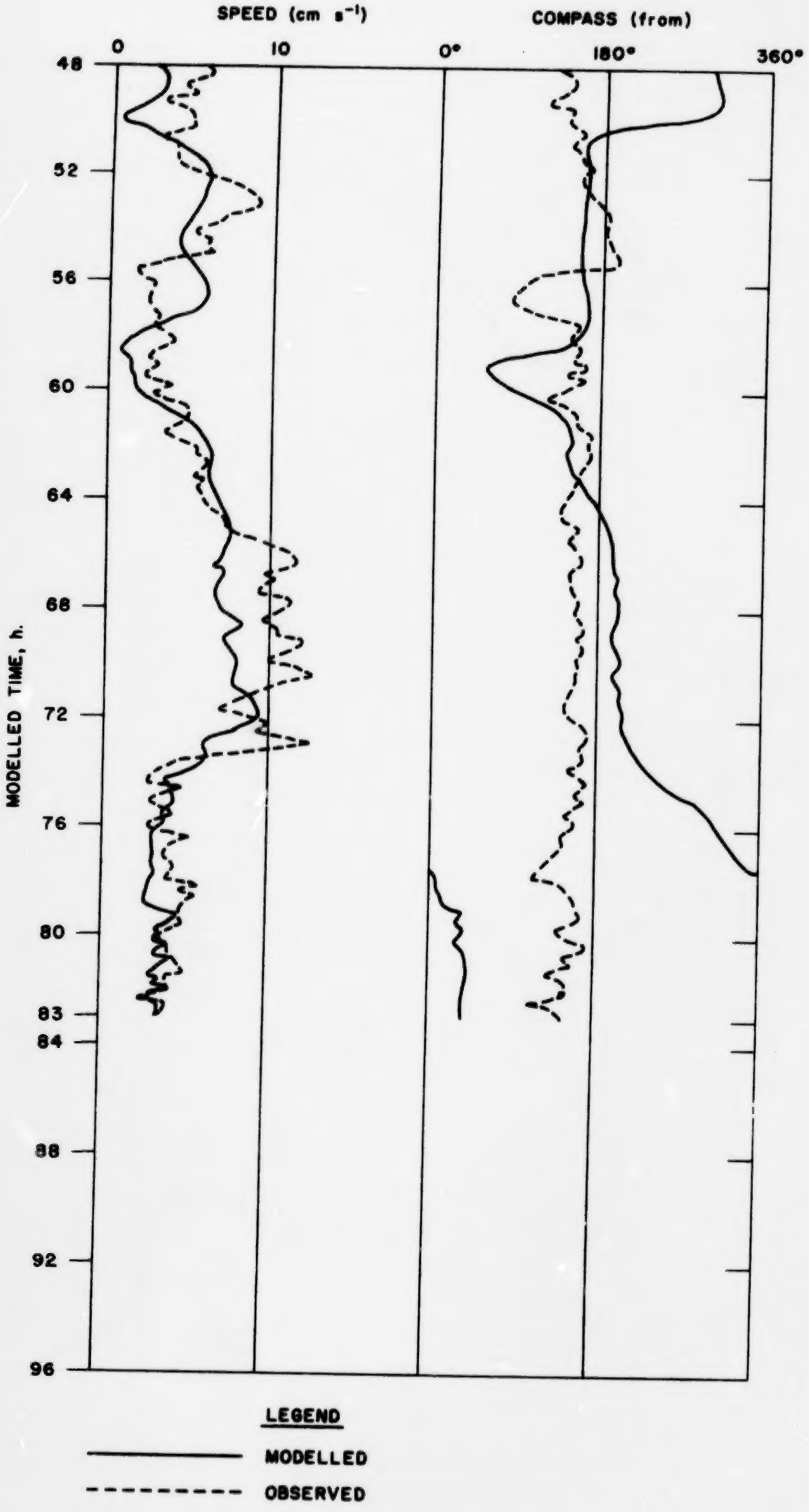


FIGURE 9b - COMPARISON OF OBSERVED AND MODELLED VELOCITIES FOR LOCATION (14,7) AND MANNING'S N = .020, .025, .030, .040, STARTING AT 1200 h. ON 740701.

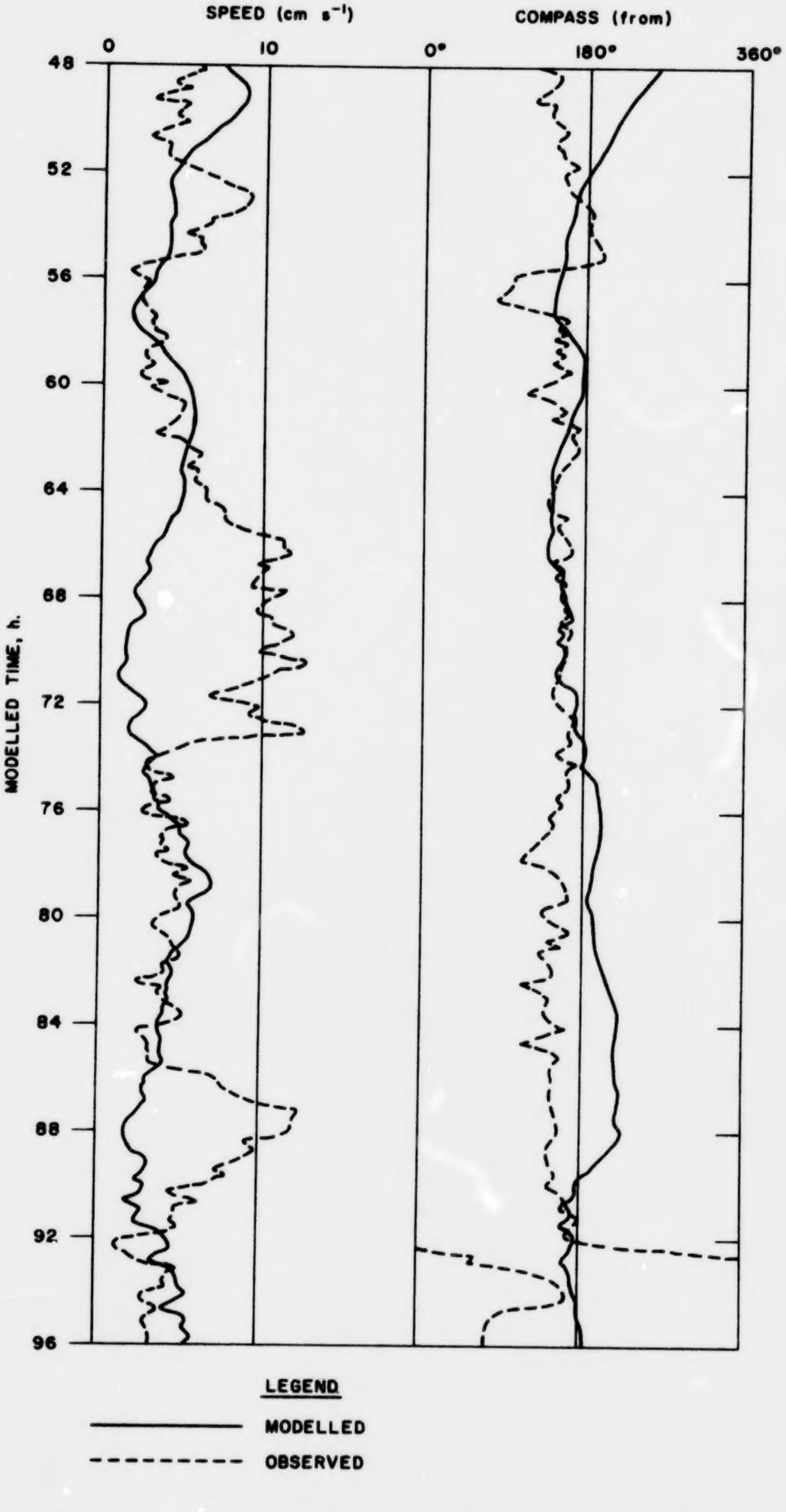


FIGURE 10 - COMPARISON OF OBSERVED AND MODELLED VELOCITIES FOR LOCATION (14,6) AND MANNING S N = .025, .030, .035, .045, STARTING AT 1200 h. ON 740701.

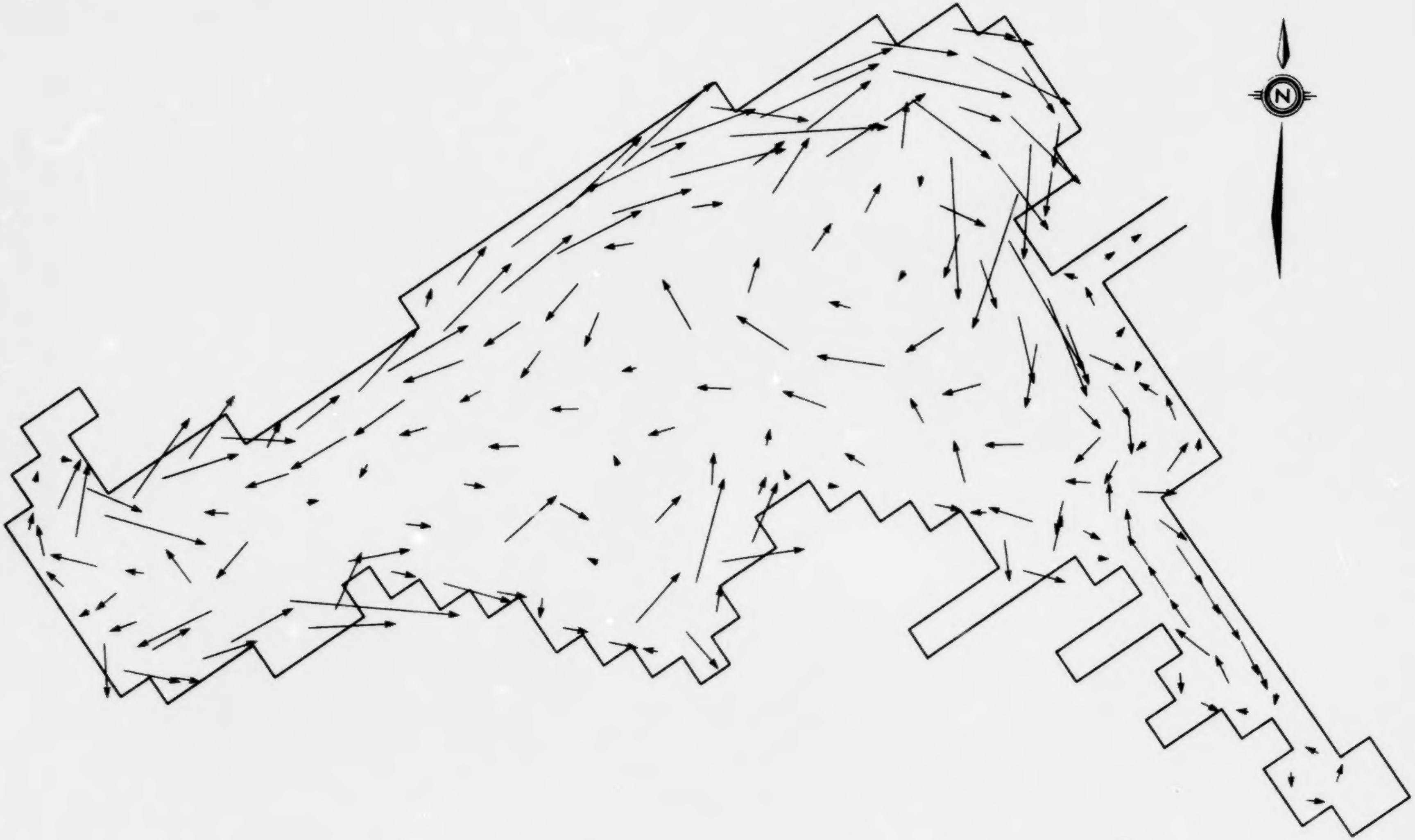


FIGURE II - NUMERICAL MODEL PREDICTION OF CURRENTS AT 54 h. MODELLED TIME.

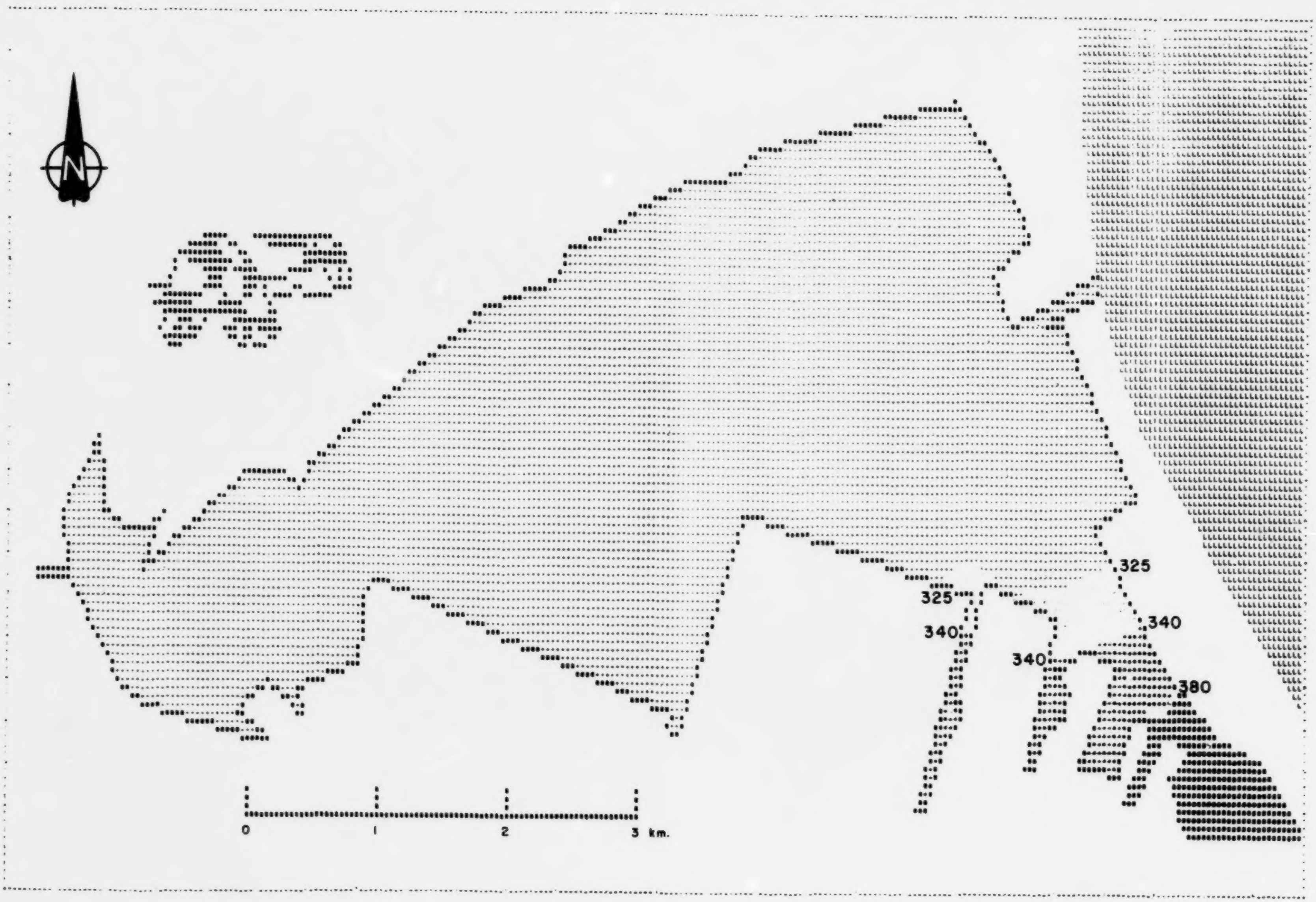

N
325
325
340
340
340
380
0
1
2
3 km.

FIGURE 12 - INITIAL TOTAL DISSOLVED SOLIDS CONCENTRATIONS (mg/L) USED IN HAMILTON HARBOUR MODEL.

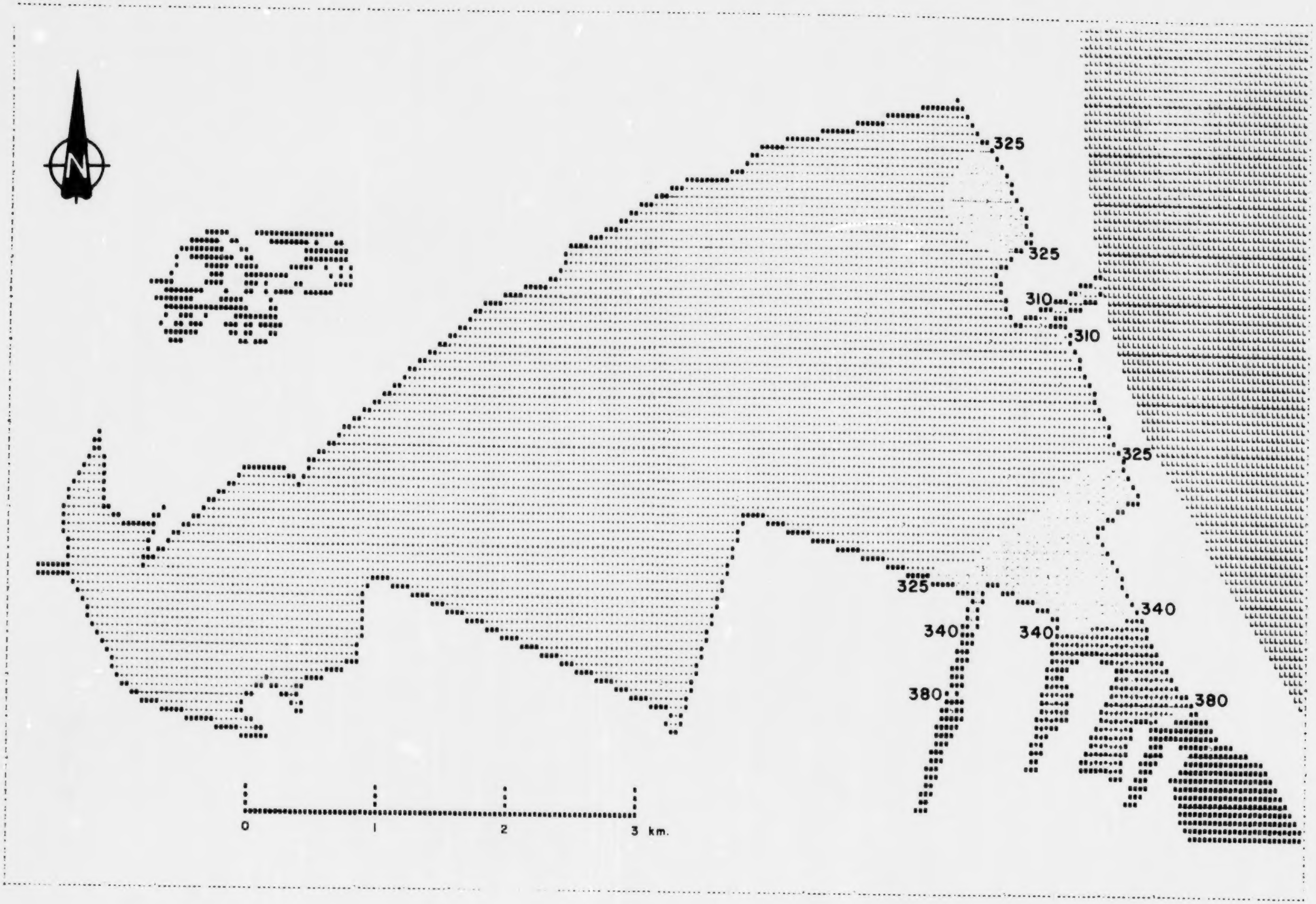
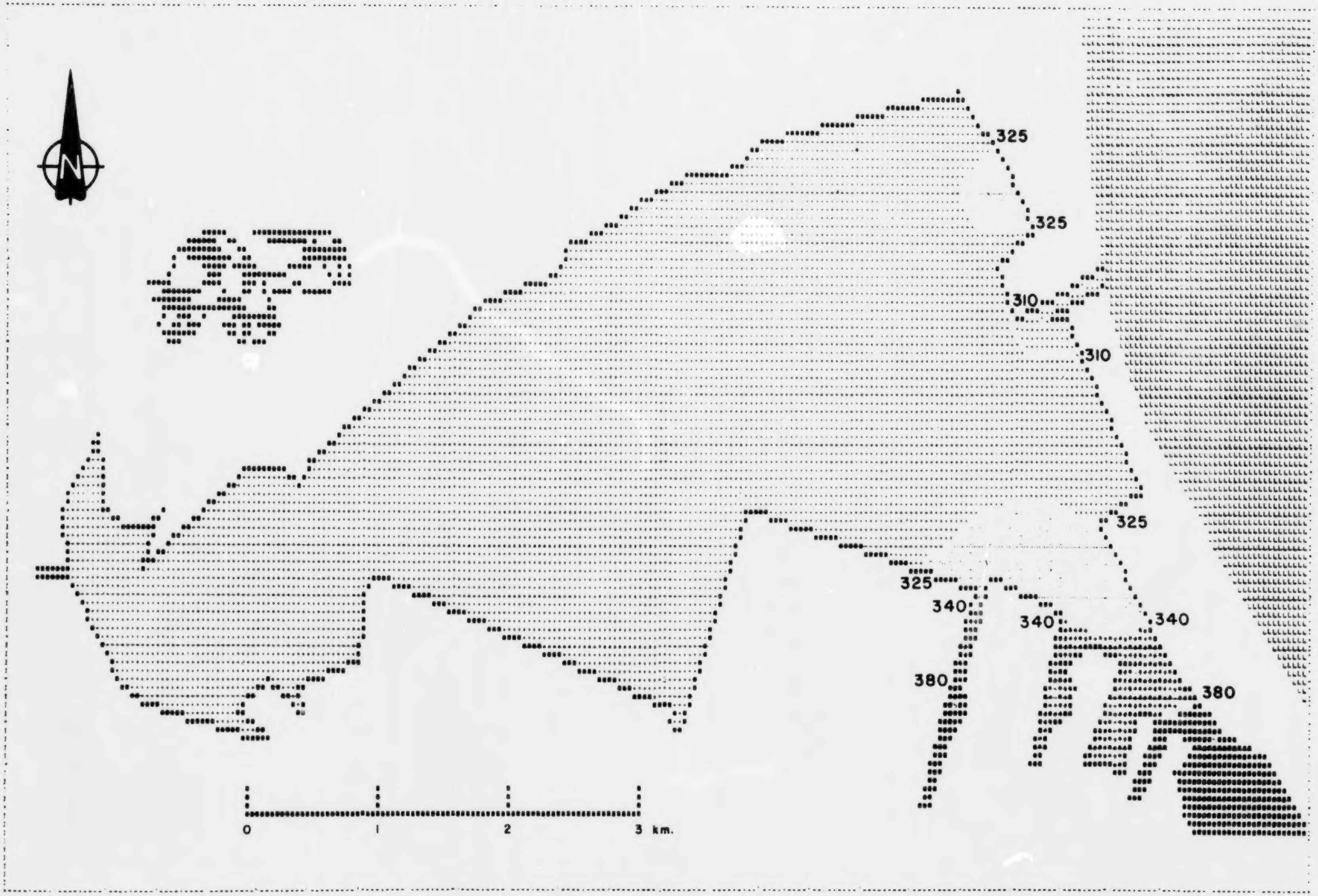

325
325
310
310
325
325
340
340
340
380
380
0
1
2
3 km.
N

FIGURE 13 - MODELLED TOTAL DISSOLVED SOLIDS CONCENTRATIONS (mg/L) AFTER 24 HOURS, HAMILTON HARBOUR.



325
325
310
310
325
325
340
340
340
380
380
0
1
2
3 km.
N

FIGURE 14 - MODELLED TOTAL DISSOLVED SOLIDS CONCENTRATIONS (mg/L) AFTER 48 HOURS, HAMILTON HARBOUR.

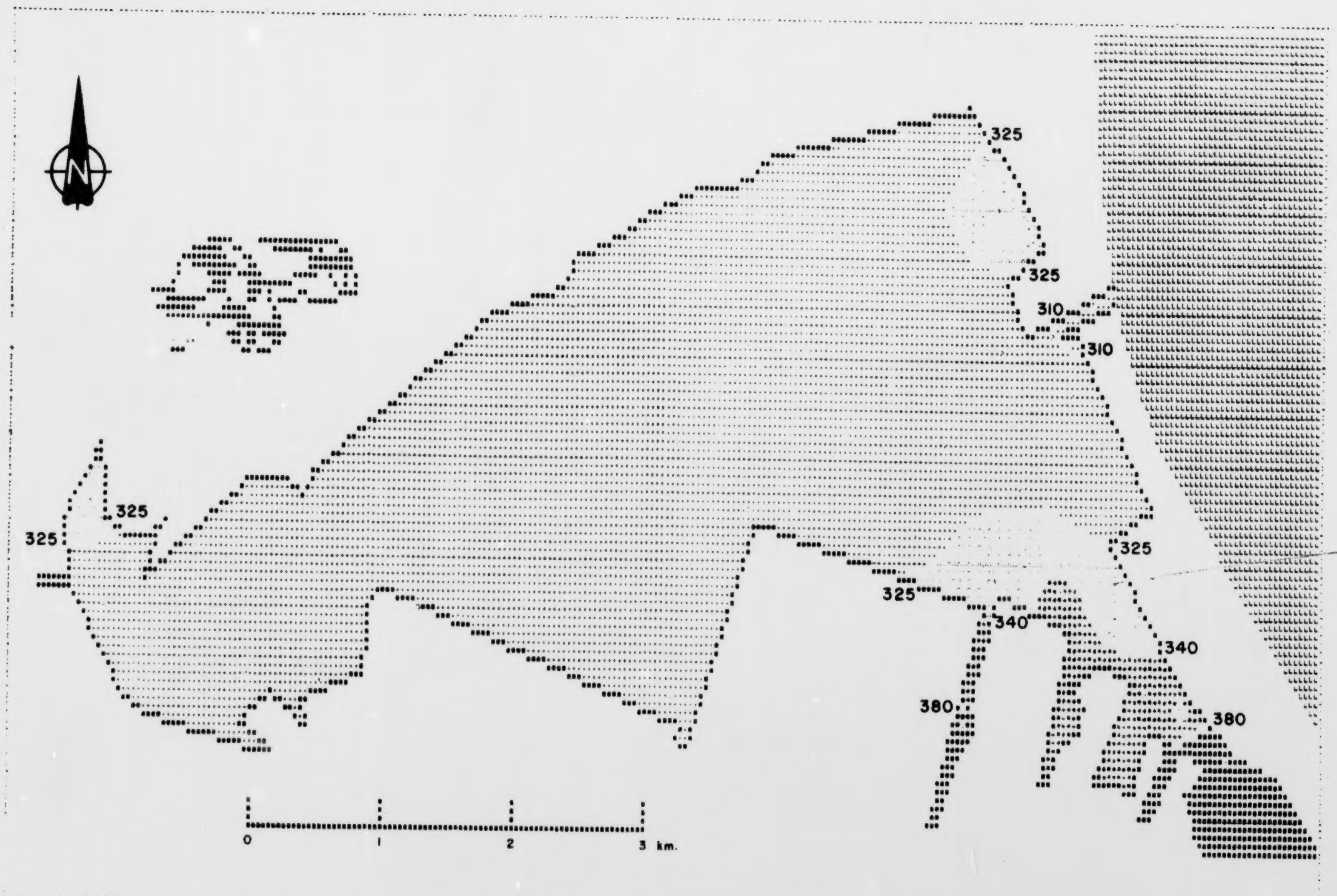

325
325
310
310
325
325
340
340
380
380
325
325
0
1
2
3 km.
N

FIGURE 15 - MODELLED TOTAL DISSOLVED SOLIDS CONCENTRATIONS (mg/L) AFTER 60 HOURS, HAMILTON HARBOUR.

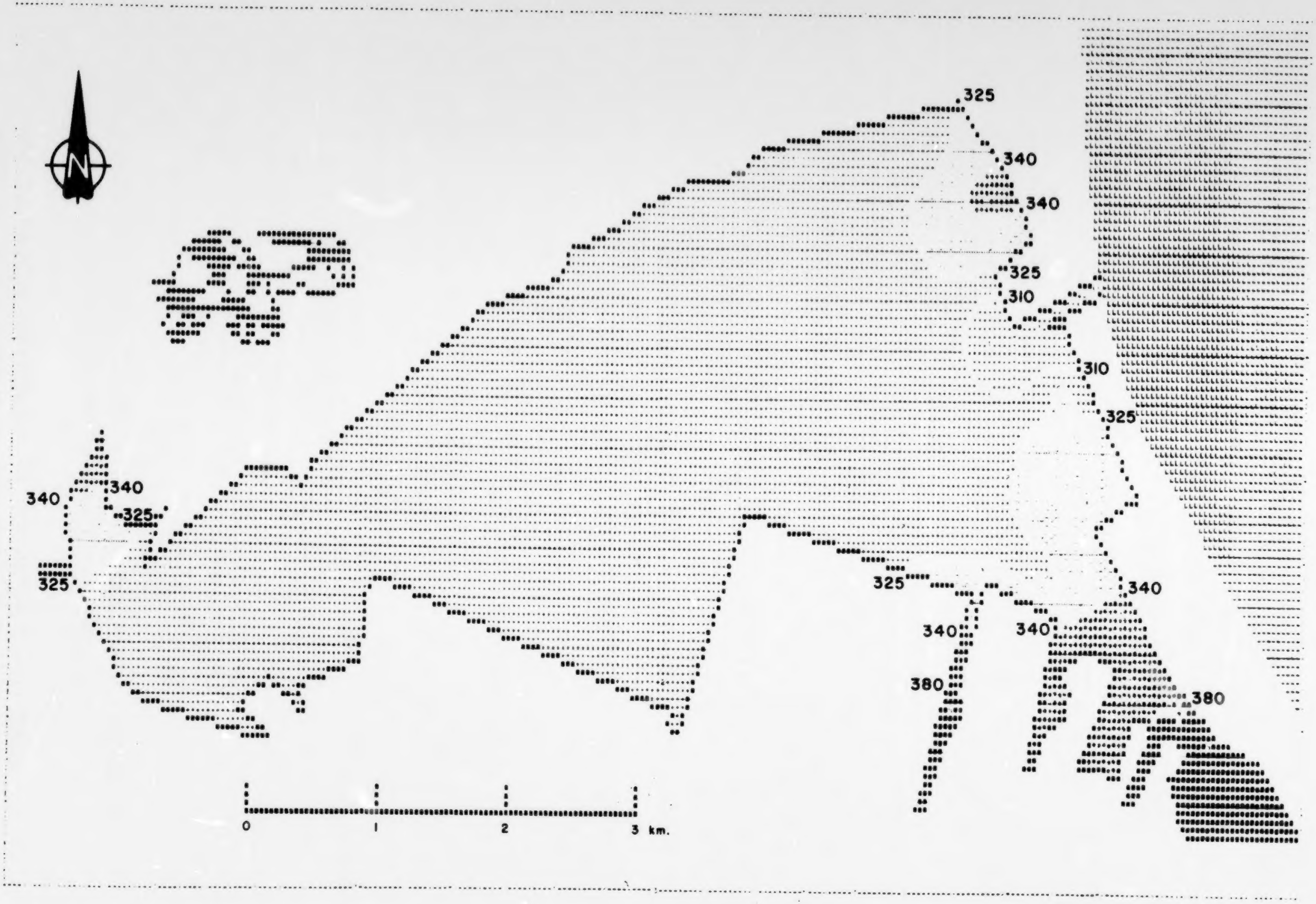

N
325
340
340
325
310
310
325
340
340
380
380
340
325
340
340
325
325
0
1
2
3 km.

FIGURE 16 - MODELLED TOTAL DISSOLVED SOLIDS CONCENTRATIONS (mg/L) AFTER 96 HOURS, HAMILTON HARBOUR.

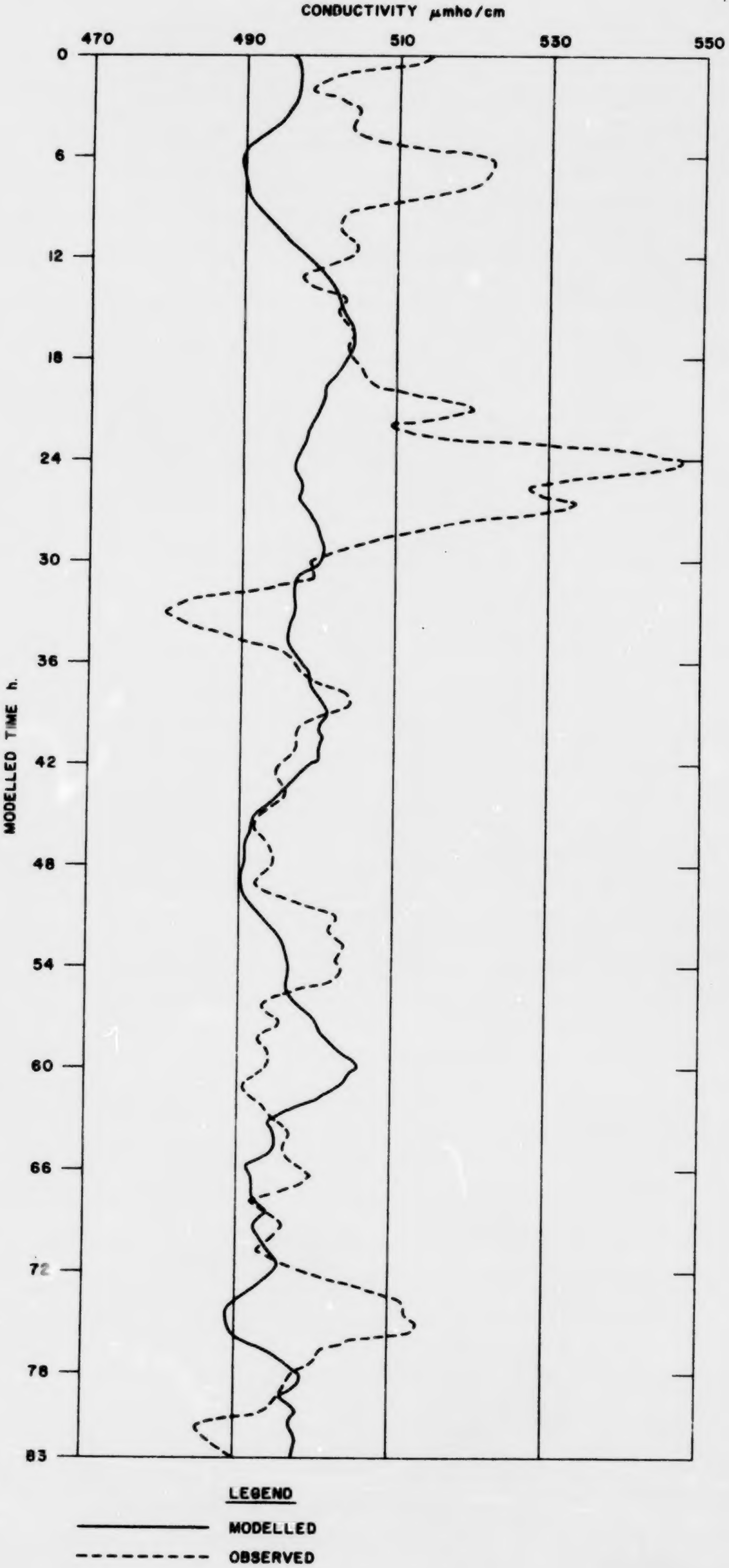


FIGURE 17 - COMPARISON OF OBSERVED (LOCATION M7) AND MODELLED CONDUCTIVITY FOR LOCATION (14,8) AND MANNING'S N = .020, .025, .030, .040, STARTING AT 1200 h. ON 740629.

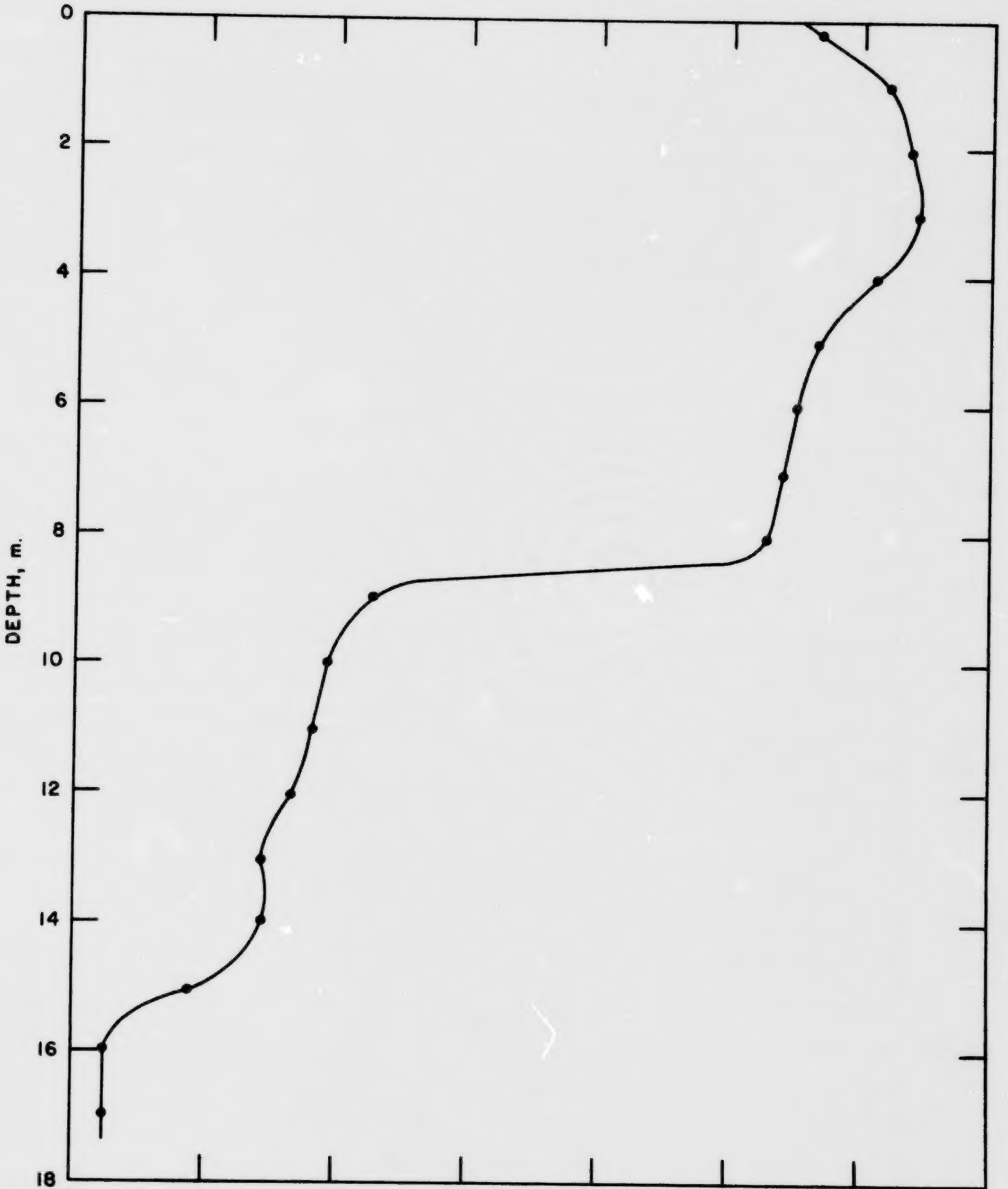


FIGURE 18 - DEPTH VARIATION OF CONDUCTIVITY, STATION 4, JULY 26, 1977.

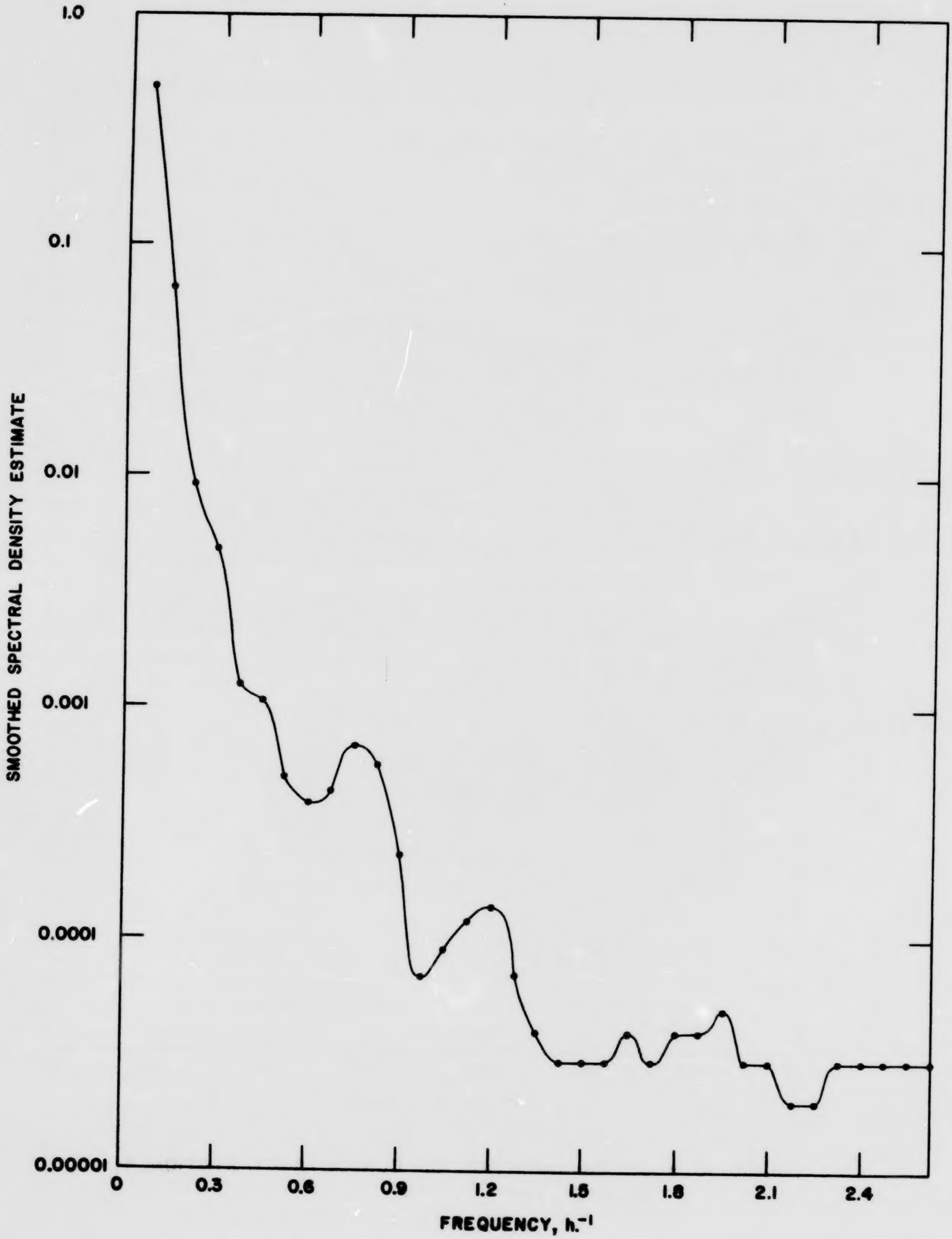


FIGURE 19 - AUTOSPECTRA OF MODELLED U VELOCITY AT LOCATION (14,8), HAMILTON HARBOUR.

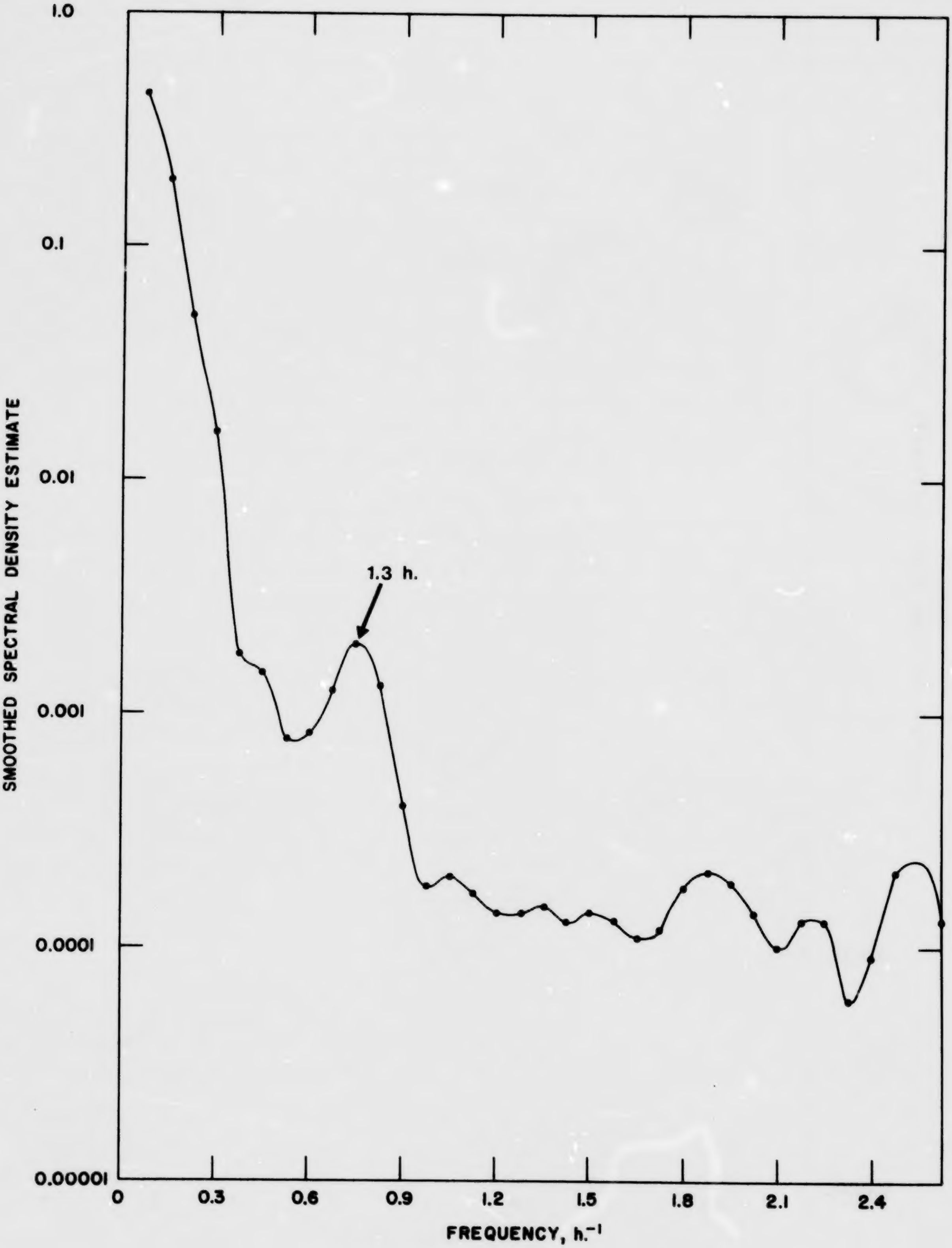


FIGURE 20 - AUTOSPECTRA OF MODELLED V VELOCITY AT LOCATION (14,8), HAMILTON HARBOUR.

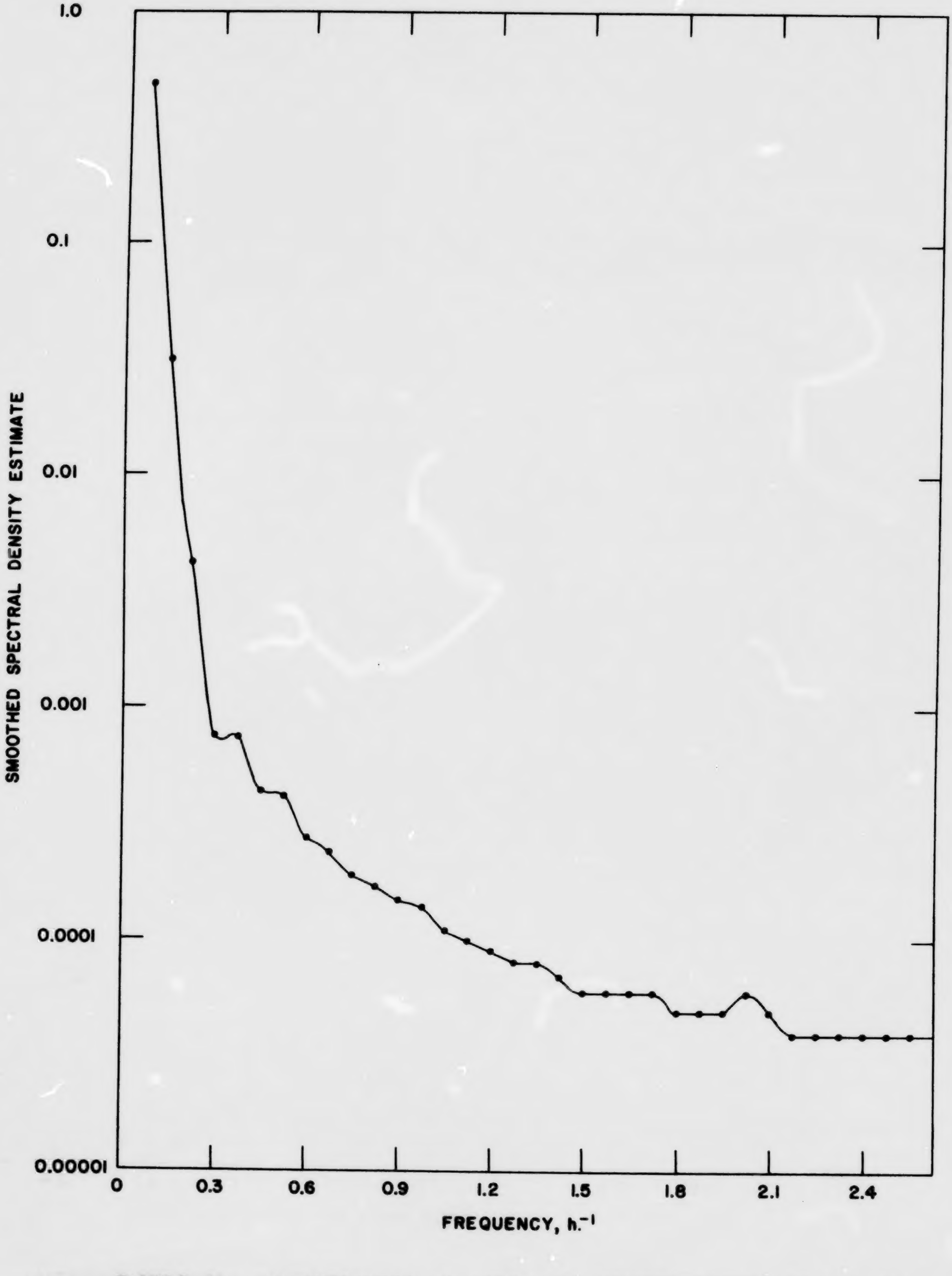


FIGURE 21 - AUTOSPECTRA OF MODELLED CONCENTRATION AT LOCATION (14,8), HAMILTON HARBOUR.

HAMILTON HARBOUR STUDY

1977

VOLUME I

SECTION G

3-DIMENSIONAL NUMERICAL MODEL

SUMMARY

The three-dimensional numerical model of hydrodynamics, temperature and water quality as developed by Leendertse et al (1973) has been modified for use on lake systems and initial calibration runs of the hydrodynamic portion have been performed for Hamilton Harbour. The theory of the model is described in detail, with particular reference to the physical parameters for which calibration values must be specified. These parameters include coefficients for surface, interfacial and bottom stress, horizontal dispersion of momentum, and horizontal and vertical diffusion of heat.

The model was operated using real-time input data for winds and currents in the Burlington Ship Canal obtained in June 1974 and June 1976. Model performance was assessed by comparing modelled currents to those measured at an internal harbour location not used in model input, and attempts were made at improving the fit to observed currents by varying the values of the input physical parameters. The best results were achieved with a wind stress coefficient of 0.020, a Chezy coefficient of bottom roughness = 700 $cm^{1/2}s^{-1}$, coefficient of interfacial friction = 1000 cm^2, and dispersion coefficient for horizontal momentum = 10^4 cm^2s^{-1}. However, modelled currents failed to follow the observed direction changes at the internal validation point; in particular, modelled middle layer currents were frequently opposite in direction to observed currents while bottom layer currents showed better agreement, despite the depth of the current meters used for validation, which corresponded to the middle layer. This suggests that because of harbour vertical instability, water flowing past the fixed current meter locations may be representative of different model layers at different times.

Based on the results obtained so far, it is suggested that future modelling works should involve a larger number of model vertical layers, as well as vertical strings of current meters for calibration processes. Such a study is ambitious and expensive, however, and its merits should be carefully reviewed before undertaking. The simpler version of the model as outlined in the report may still be useful for a description of the effect of changing wind and lake conditions on average harbour currents, as illustrated by a series of computerized plots of modelled currents.

INTRODUCTION

The development of a 2-dimensional model was included as a portion of the original Hamilton Harbour Study objectives (MOE, 1974). This model involved predictions of depth-integrated currents and total dissolved solids (TDS). The model has been extended (Section F) by adding input of currents and TDS values at the major waste sources (Hamilton STP and Ottawa Street slip) and at the open boundary (Burlington Ship Canal) at short-time scale intervals of 10 to 20 minutes. These short intervals were required for adequate description of the rapidly varying conditions which were found to exist, particularly in the Burlington Ship Canal.

Comparison of observed and modelled currents at an internal validation point showed inadequate agreement, with predicted currents opposite in direction to those observed for a portion of the modelled interval. It was concluded that errors were primarily caused by the use of a 2-dimensional depth-integrated model to describe a thermally stratified (June-July) condition, and that a 3-dimensional model would provide an improved simulation. The present report summarizes initial efforts at applying a 3-dimensional model to the problem of Hamilton Harbour circulation under conditions of summer stratification.

THEORY

Larger scale water motions in lakes are primarily caused by wind and modified by interfacial and bottom friction stresses. Motion due to inflows and outflows of water is normally observable only immediately adjacent to these flows. As natural lake basins are geometrically very complicated and wind motions highly variable both in space and time, an exact description of 3-dimensional time-dependant motions would require an infinite number of parameters.

FORMULATION

These fluid motions may be described by the classical hydrodynamic equations of momentum, continuity and mass transport (Leendertse, Alexander and Liu, 1973; Lick, 1976; Cheng, Powell and Dillon, 1976). These are conceptually similar to the 2-dimensional equations previously used in Hamilton Harbour (MOE, 1974), and are as follows:

(a) Momentum equations

$$\frac{\partial u}{\partial t} + \frac{\partial (uu)}{\partial x} + \frac{\partial (uv)}{\partial y} + \frac{\partial (uw)}{\partial z} - fv + \frac{1}{\rho}\frac{\partial p}{\partial x} - \frac{1}{\rho}\left[\frac{\partial}{\partial x}\left(A_H \frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(A_H \frac{\partial u}{\partial y}\right) + \frac{\partial}{\partial z}\left(A_V \frac{\partial u}{\partial z}\right)\right] = 0 \qquad (1)$$

[A] [B] [C] [D] [E] [F]

$$\frac{\partial v}{\partial t} + \frac{\partial (uv)}{\partial x} + \frac{\partial (vv)}{\partial y} + \frac{\partial (vw)}{\partial z} + fu + \frac{1}{\rho}\frac{\partial p}{\partial y} - \frac{1}{\rho}\left[\frac{\partial}{\partial x}\left(A_H \frac{\partial v}{\partial x}\right) + \frac{\partial}{\partial y}\left(A_H \frac{\partial v}{\partial y}\right) + \frac{\partial}{\partial z}\left(A_V \frac{\partial v}{\partial z}\right)\right] = 0 \qquad 2)$$

$$\frac{\partial p}{\partial z} + \rho g = 0 \qquad 3)$$

The symbols used will be defined below; the significance of the terms in equations (1) and (2) is as follows:

[A] Variation of velocity component with time.

[B] Convective transports of momentum in the x-, y-, and z-directions. In larger water bodies like Lake Ontario, these terms are often neglected with resulting simplification of computations (Csanady, 1978). This approximation is reasonable when the Rossby number is less than about 0.1 (Cheng et al, 1976). For Hamilton Harbour, a Rossby number of 0.1 corresponds to a current speed of about 8 cm s^{-1}; therefore these terms should be included for computational accuracy, though James and Eid (1978) chose to neglect them.

[C] Coriolis force due to earth's rotation.

[D] Momentum change due to pressure variations in x- and y-directions. These pressure variations are caused by water level differences induced by wind set-up.

[E] Horizontal dispersive transport of momentum. These terms approximate the horizontal sub-grid scale turbulent stresses (Reynolds stresses).

[F] Vertical dispersive transport of momentum. This term includes the effect of frictional stresses at the water surface and bottom, and between layers in the vertical.

The vertical equation of momentum has been replaced by the hydrostatic approximation equation (3), as vertical accelerations may be neglected compared to horizontal accelerations.

(b) Continuity equation (conservation of water volume).

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \qquad (4)$$

The terms of this equation express the changes in water volume due to velocity changes in each direction. This assumes that water is incompressible, and that density variations are allowed to affect only the vertical acceleration (Boussinesq approximation).

(c) Mass and heat transport equations

$$\frac{\partial s}{\partial t} + \frac{\partial (us)}{\partial x} + \frac{\partial (vs)}{\partial y} + \frac{\partial (ws)}{\partial z} - \frac{\partial}{\partial x}\left(D_x \frac{\partial s}{\partial x}\right) - \frac{\partial}{\partial y}\left(D_y \frac{\partial s}{\partial y}\right) - \frac{\partial}{\partial z}\left(\kappa \frac{\partial s}{\partial z}\right) = 0 \qquad (5)$$

[A] [B] [C]

$$\frac{\partial T}{\partial t} + \frac{\partial (uT)}{\partial x} + \frac{\partial (vT)}{\partial y} + \frac{\partial (wT)}{\partial z} - \frac{\partial}{\partial x}\left(D_x \frac{\partial T}{\partial x}\right) - \frac{\partial}{\partial y}\left(D_y \frac{\partial T}{\partial y}\right) - \frac{\partial}{\partial z}\left(\kappa' \frac{\partial T}{\partial z}\right) = 0 \qquad (6)$$

[A] variation of mass or heat with time.

[B] advective transport of mass or heat in the x-, y-, and z-directions.

[C] diffusion of mass or heat in the x-, y-, and z- directions.

Equation (5) may be used for non-conservative substances (dissolved oxygen, BOD, bacteria, etc.) upon insertion of the approporiate decay terms.

(d) Equation of state

$$\rho = \bar{\rho} + \rho' (T) \tag{7}$$

This equation expresses density changes as a function of temperature. In fresh water environments, small density changes due to dissolved solids may be neglected.

The symbols in equations (1) - (7) are as follows:

x, y, z	Cartesian coordinates positive eastward, northward, and upward, respectively
u, v, w	Respective components of velocity
t	Time
f	Coriolis parameter
p	Pressure
s	Dissolved solids concentration
T	Temperature
ρ	Density
$\bar{\rho}$	Reference density, a constant
ρ'	Departure from $\bar{\rho}$ depending on temperature
g	acceleration due to gravity
κ	Vertical mass diffusion coefficient
κ'	vertical thermal diffusion coefficient
A_H, A_V	Horizontal and vertical eddy viscosity coefficients
Dx, Dy	Horizontal diffusion coefficients

These equations as written above introduce no internal sources of momentum, fluid or solids; in the case of a harbour receiving waste discharges, appropriate source terms must be added. To complete the description of the model, appropriate initial and boundary conditions are added. The initial condition states that all velocities and water levels are zero; alternately, the final velocity pattern from a previous run (such as a spin-up) may be used as an initial condition. Boundary conditions require the specification of current, temperatures and salinities at all open boundaries (such as the Burlington Ship Canal); the input used for open boundaries is discussed in detail later. At closed (land) boundaries, the boundary condition is that all velocity components normal to the land boundary are zero.

VERTICAL DISCRETIZATION

In thermally stratified lakes and harbours, considerable changes can occur in the properties described by equations (1) - (6) within a short vertical distance. In order to achieve a reasonable approximation to this vertical variation within a finite amount of computer time and memory, the water body is divided into a number of discrete layers and the above equations are vertically integrated over the thickness of each layer. This vertical integration procedure is described by Leendertse, Alexander and Liu (1973); it suffices here to present the vertically integrated equations along with the assumptions used in their derivation together with the appropriate initial and boundary conditions.

$$\begin{aligned}\frac{\partial(hu)}{\partial t} + \frac{\partial(huu)}{\partial x} + \frac{\partial(huv)}{\partial y} + (wu)_{k-\frac{1}{2}} - (wu)_{k+\frac{1}{2}} - fhv + \frac{h}{\rho}\frac{\partial P}{\partial x} \\ - \frac{1}{\rho}\frac{\partial}{\partial x}\left(h\,A_H\,\frac{\partial u}{\partial x}\right) - \frac{1}{\rho}\frac{\partial}{\partial y}\left(h\,A_H\,\frac{\partial u}{\partial y}\right) - \left(\frac{1}{\rho}\,\tau^{xz}\right)_{k-\frac{1}{2}} + \left(\frac{1}{\rho}\,\tau^{xz}\right)_{k+\frac{1}{2}} = 0\end{aligned} \tag{8}$$

$$\begin{aligned}\frac{\partial(hv)}{\partial t} + \frac{\partial(hvu)}{\partial x} + \frac{\partial(hvv)}{\partial y} + (wv)_{k-\frac{1}{2}} - (wv)_{k+\frac{1}{2}} + fhu + \frac{h}{\rho}\frac{\partial P}{\partial y} \\ - \frac{1}{\rho}\frac{\partial}{\partial x}\left(h\,A_H\,\frac{\partial v}{\partial x}\right) - \frac{1}{\rho}\frac{\partial}{\partial y}\left(h\,A_H\,\frac{\partial v}{\partial y}\right) - \left(\frac{1}{\rho}\,\tau^{yz}\right)_{k-\frac{1}{2}} + \left(\frac{1}{\rho}\,\tau^{yz}\right)_{k+\frac{1}{2}} = 0\end{aligned} \tag{9}$$

$$w_{k-\frac{1}{2}} = -\sum_{\ell=k}^{h}\left(\frac{\partial(hu)}{\partial x} + \frac{\partial(hv)}{\partial y}\right) \qquad k > 1 \tag{10a}$$

$$\frac{\partial\zeta}{\partial t} = -\sum_{\ell=1}^{h}\left(\frac{\partial(hu)}{\partial x} + \frac{\partial(hv)}{\partial y}\right) + F \qquad k=1 \tag{10b}$$

$$\frac{\partial(hs)}{\partial t} + \frac{\partial(hus)}{\partial x} + \frac{\partial(hvs)}{\partial y} + (ws)_{k-\frac{1}{2}} - (ws)_{k+\frac{1}{2}} - \frac{\partial}{\partial x}\left(h\, D_x \frac{\partial s}{\partial x}\right) - \frac{\partial}{\partial y}\left(h\, D_y \frac{\partial s}{\partial y}\right) - \left(\kappa \frac{\partial s}{\partial z}\right)_{k-\frac{1}{2}} + \left(\kappa \frac{\partial s}{\partial z}\right)_{k+\frac{1}{2}} + sF = 0 \tag{11}$$

$$\frac{\partial(hT)}{\partial t} + \frac{\partial(huT)}{\partial x} + \frac{\partial(hvT)}{\partial y} + (wT)_{k-\frac{1}{2}} - (wT)_{k+\frac{1}{2}} - \frac{\partial}{\partial x}\left(h\, D_x \frac{\partial T}{\partial x}\right) - \frac{\partial}{\partial y}\left(h\, D_y \frac{\partial T}{\partial y}\right) - \left(\kappa \frac{\partial T}{\partial z}\right)_{k-\frac{1}{2}} + \left(\kappa \frac{\partial T}{\partial z}\right)_{k+\frac{1}{2}} + TF = 0 \tag{12}$$

In these equations, the quantities u, v, w, s, t and p are vertical averages over the layer k under consideration. A subscript $k - \frac{1}{2}$ or $k + \frac{1}{2}$ represents a valve calculated at the interface between layer k and layer k -1 or k +1, respectively. See figure 1 for configuration of layers.

In addition, τ^{xz} and τ^{yz} = components of surface, interfacial or bottom stress.

ℓ = any layer
k = layer being computed
b = bottom layer
ζ = water level displacement from equilibrium level
h = thickness of layer
F = rate of water level increase due to addition of water at waste source point (= flow rate divided by area of grid square into which discharge flows).

The last term in equations (10b), (11) and (12) represents the addition of water, pollutant and heat, respectively, to the system from an outfall or its removal at an intake. An intake is represented by a negative F value. At present, all outfalls and intakes are assumed to be at the surface level (k = 1).

SPECIFICATION OF PRESSURE AND STRESS TERMS

Equations (8) - (12) contain stress terms which must be evaluated for every model layer as part of the boundary conditions for model solution. As the value of these terms is determined by physical constants whose value must be specified for model calibration, their evaluation will be presented in some detail.

The pressure gradients in equations (8) and (9) are defined for the top layer (k = 1) as :

$$\frac{\partial P_1}{\partial x} = g\rho_1 \frac{\partial \zeta}{\partial x} + \tfrac{1}{2}\, gh_1 \frac{\partial \rho_1}{\partial x} \tag{13a}$$

$$\frac{\partial P_1}{\partial y} = g\rho_1 \frac{\partial \zeta}{\partial y} + \tfrac{1}{2}\, gh_1 \frac{\partial \rho_1}{\partial y} \tag{13b}$$

For the other layers ($k > 1$) the pressure gradient is given by

$$\frac{\partial P_k}{\partial x} = \frac{\partial P_{k-1}}{\partial x} + gh_{k-\frac{1}{2}} \frac{\partial \rho_{k-\frac{1}{2}}}{\partial x} \tag{14a}$$

$$\frac{\partial P_k}{\partial y} = \frac{\partial P_{k-1}}{\partial y} + gh_{k-\frac{1}{2}} \frac{\partial \rho_{k-\frac{1}{2}}}{\partial y} \tag{14b}$$

In the equations the subscript $k - \frac{1}{2}$ represents an average of the value between layers $k - 1$ and k. The above equations are derived on the asumption that the spatial variation of atmospheric pressure across the water body is negligible.

The stress terms $\tau^{xz}_{k+\frac{1}{2}}$, $\tau^{xz}_{k-\frac{1}{2}}$, $\tau^{yz}_{k+\frac{1}{2}}$, and $\tau^{yz}_{k-\frac{1}{2}}$ in equations (8) and (9), which arise from the vertical dispersion terms [F] in equations (1) and (2), require careful and complete consideration as the model solution is highly sensitive to their values, which are determined in part by the choice of physical parameters contained therein. For the top layer (k = 1), the terms $\tau^{xz}_{k+\frac{1}{2}}$ and $\tau^{yz}_{k-\frac{1}{2}}$ represent the effect of wind stress at the air-water interface. At the bottom (k = b), the terms $\tau^{xz}_{k+\frac{1}{2}}$ and $\tau^{yz}_{k+\frac{1}{2}}$ represent the frictional effect of water moving over the sediment-water interface. At intermediate layers, these terms represent turbulent effects due to interlayer density and velocity differences. Each term will be considered in detail.

The surface stress terms are represented by quadratic functions of wind velocity as follows:

$$\tau^{xs} = \Theta \rho_a \; W_a^2 \sin \Psi \tag{15a}$$

$$\tau^{ys} = \Theta \rho_a \; W_a^2 \cos \Psi \tag{15b}$$

where s (superscript) = surface

Θ = wind-stress coefficient
ρ_a = density of air
W_a = wind speed
Ψ = angle between wind direction and the model y - axis

The bottom stress terms can also be represented by quadratic expressions:

$$\tau^{xb} = \frac{\rho g \; u \; (u^2 + v^2)^{\frac{1}{2}}}{C} \tag{16a}$$

$$\tau^{yb} = \frac{\rho g \; v \; (u^2 + v^2)^{\frac{1}{2}}}{C} \tag{16b}$$

where b (superscript) = bottom layer
g = acceleration due to gravity
C = Chezy's coefficient of bottom roughness (dimension $L^{\frac{1}{2}} T^{-1}$)

Chezy's coefficient in equation (14) can in turn be expressed as a function of total water depth H by the Manning equation:

$$C = \frac{1.49}{n} \; H^{1/6} \tag{17}$$

where n = Manning's constant (dimension $L^{-1/3} T$)

The corresponding stress terms in the constituent and heat balance equations (11) and (12) must also be considered. For a conservative substance in equation (11), these terms are zero. For heat, the surface term $\left(\kappa' \frac{\partial T}{\partial Z}\right)_{k-\frac{1}{2}}$ for k = 1 represents heat flux at the surface. An exact specification of this term requires that it consider heat transfer by mechanisms such as radiation, convection and evaporation, which are all time varying. A simplified expression for heat flux q at the surface (Lick, 1976) is dependent only upon the air temperature T_a and the model surface layer temperature T_1. Integrated over the model surface layer, this expression becomes:

$$\left(\kappa' \frac{\partial T}{\partial z}\right)_s = q = Hh_1 \left(T_1 - T_a\right) \tag{18}$$

where q = heat flux at the surface
H = surface heat transfer coefficient
h_1 = thickness of model surface layer

At the bottom, a similar heat transfer coefficient may be used if the sediment temperature is known or assumed. Alternately, the heat flux can be considered as zero for the length of model operation used here.

Several approaches were considered by Leendertse and Liu (1975) for the interfacial stress terms, which can be written simply for dissolved solids, temperature, x-, and y- momentum respectively as follows (see equations 8, 9, 11 and 12):

$$\kappa \frac{\partial s}{\partial z},\ \kappa' \frac{\partial T}{\partial z},\ \tau^{xz} \text{ and } \tau^{yz}$$

The stress terms τ^{xz} and τ^{yz} arise from vertical integration of the vertical eddy viscosity terms [F] in equations (1) and (2). These terms are proportional to the velocity gradient in the vertical direction (see equations (1) and (2)); the proportionality constant is the eddy viscosity coefficient A_V. The sub-grid scale vertical turbulent fluctuations are then assumed to appear as increased viscous flow stresses (Reynolds stresses). Eddy conductivity coefficients are similarly introduced so that mass and heat fluxes are proportional to concentration and temperature gradients, respectively. In turbulent flow, these coefficients also depend upon the flow itself as this is the process generating the turbulence.

In constant-density systems, the eddy viscosity coefficients may be represented by quadratic terms similar to those used for surface and bottom stress (Leendertse, Alexander and Liu, 1973):

$$A_V \frac{\partial U}{\partial Z} = \left(\frac{1}{\rho} \tau^{xz}\right)_{k+\frac{1}{2}} = \nu_1 \frac{\Delta U}{\Delta Z} \left\{\left(\frac{\Delta U}{\Delta Z}\right)^2 + \left(\frac{\Delta V}{\Delta Z}\right)^2\right\}^{\frac{1}{2}} \tag{19a}$$

$$A_V \frac{\partial V}{\partial Z} = \left(\frac{1}{\rho} \tau^{yz}\right)_{k+\frac{1}{2}} = \nu_1 \frac{\Delta V}{\Delta Z} \left\{\left(\frac{\Delta U}{\Delta Z}\right)^2 + \left(\frac{\Delta V}{\Delta Z}\right)^2\right\}^{\frac{1}{2}} \tag{19b}$$

$$\left(\kappa \frac{\partial s}{\partial z}\right) = \kappa_1 \frac{\Delta s}{\Delta Z} \left\{\left(\frac{\Delta U}{\Delta Z}\right)^2 + \left(\frac{\Delta V}{\Delta Z}\right)^2\right\}^{\frac{1}{2}} \tag{19c}$$

$$\left(\kappa' \frac{\partial T}{\partial Z}\right) = \kappa_1' \frac{\Delta T}{\Delta Z} \left\{\left(\frac{\Delta U}{\Delta Z}\right)^2 + \left(\frac{\Delta V}{\Delta Z}\right)^2\right\}^{\frac{1}{2}} \tag{19d}$$

Corresponding to the discrete depth formulation of Figure A, the partial differentials $\partial/\partial z$ have been replaced by the difference $\Delta/\Delta z$ between the centers of the layers. The parameters ν , κ_1 , and κ_1' , are coefficients of interfacial friction. These coefficients (dimension L^2) are the squares of the Prandtl's mixing lengths for momentum, salinity and temperature (Odd & Roger, 1978, equation 2). Increased turbulence (increased A_V) manifests itself in an increased value of these coefficients.

When vertical density gradients exist, the intensity of the turbulence is also affected by the buoyancy forces induced by the density gradient. Increased stratification suppresses turbulence; the onset of this suppression may be determined from the value of the Richardson number, as follows:

$$Ri = \frac{g \ (\partial\rho/\partial z)}{\rho \ (\partial U/\partial z)^2} \tag{20}$$

where U is the velocity component under considerations for u and v velocity calculations or the resultant velocity for temperature and concentration calculations. Turbulence is maintained at Ri values below about 0.25 and suppressed at larger Ri values.

Leendertse and Liu (1975) investigated several formulas relating interfacial stress to the Richardson number, and selected an exponential form proposed by Mamayev (1958; cited by Leendertse and Liu, 1975):

$$\nu = \nu_o e^{-mRi} \tag{21a}$$

$$\kappa = \kappa' = \nu_o e^{-rRi} \tag{21b}$$

Values of 1.5 and 3.0 were suggested for the empirical coefficients m and r, respectively; ν_o is the vertical momentum transfer coefficient under neutral stability (Ri = 0).

These two contributions to vertical eddy viscosity are combined in the present model to yield expressions for the τ and κ terms in equations (8), (9), (11) and (12) as follows:

$$\left(\frac{1}{\rho}\tau^{xz}\right)_{k+\frac{1}{2}} = \left\{\nu_o \quad \exp(-m.Ri) + \nu_1\left[\left(\frac{\Delta U}{\Delta Z}\right)^2 + \left(\frac{\Delta V}{\Delta Z}\right)^2\right]^{\frac{1}{2}}\right\}\left(\frac{\Delta U}{\Delta Z}\right) \tag{22a}$$

$$\left(\frac{1}{\rho}\tau^{yz}\right)_{k+\frac{1}{2}} = \left\{\nu_o \quad \exp(-m.Ri) + \nu_1\left[\left(\frac{\Delta U}{\Delta Z}\right)^2 + \left(\frac{\Delta V}{\Delta Z}\right)^2\right]^{\frac{1}{2}}\right\}\left(\frac{\Delta V}{\Delta Z}\right) \tag{22b}$$

$$\left(\kappa\frac{\Delta S}{\Delta Z}\right)_{k+\frac{1}{2}} = \left\{\nu_o \quad \exp(-r.Ri) + \kappa_1\left[\left(\frac{\Delta U}{\Delta Z}\right)^2 + \left(\frac{\Delta V}{\Delta Z}\right)^2\right]^{\frac{1}{2}}\right\}\left(\frac{\Delta S}{\Delta Z}\right) \tag{22c}$$

$$\left(\kappa'\frac{\Delta T}{\Delta Z}\right)_{k+\frac{1}{2}} = \left\{\nu_o \quad \exp(-r.Ri) + \kappa_1'\left[\left(\frac{\Delta U}{\Delta Z}\right)^2 + \left(\frac{\Delta V}{\Delta Z}\right)^2\right]^{\frac{1}{2}}\right\}\left(\frac{\Delta T}{\Delta Z}\right) \tag{22d}$$

The differences are taken between layers k and k+1 for subscript $k+\frac{1}{2}$; for subscript $k-\frac{1}{2}$ they are taken between layers $k-\frac{1}{2}$ and k . The coefficients ν_o, ν_1, κ_1 and κ_1', occurring in the above equations are defined above, and their values must be specified as part of the physical constants affecting model calibration.

The effect of stratification ($Ri > 0$) of the interfacial stress is thus seen as equivalent to a decrease in the value of the coefficient of interfacial friction. This is physically equivalent to a higher surface water velocity, and lower subsurface return velocities (but return velocities occurring over a larger portion of the water column).

In addition to these vertical stress terms, there also exists the horizontal eddy viscosity terms [E] in equations (1) and (2). The eddy viscosity A_H is another physical parameter to be specified during model calibration; an increased A_H results in considerable smoothing of the horizontal velocities (Simons, 1971). The effect of this parameter, however, is generally less than that of A_V (Simons, 1974); it is often omitted from hydrodynamic models, including the 2-dimensional Hamilton Harbour model (MOE, 1974).

FINITE-DIFFERENCE FORMULATIONS

As with the 2-dimensional model (MOE, 1974), the coupled system of equations (8) - (12) is solved numerically by a finite-difference method based upon the space-staggered grid lattice shown in Figure 1. In this grid the indices i, j and k represent single steps along the grid lattice in the directures x, y and z respectively. Temperatures and concentrations are calculated at integer values i, j and k; u velocity components are calculated at half-integer values of i and integer values of j and k; v velocity components are calculated at half-integer values of k and integer values of i and j; and w velocity components are calculated at half-integer values of k and integer values of i and j. The resulting finite-difference expressions for equations (8) - (12) are described by Leendertse, Alexander and Liu (1973, 1975), and will not be repeated here.

Several different integration methods are available for solution of the finite-difference equations. The integration schemes must meet three basic requirements (Cheng et al, 1976): (a) they must be numerically stable; (b) the wave motions must not decay in time when the dissipation terms are deleted from the governing equations; and (c) quadratic properties like total kinetic energy must be conserved. Although the alternating-direction implicit (ADI) method used in the 2-dimensional model satisfies these criteria with a longer time-step than that allowed by explicit methods, the ADI method requires large computer memory and is subject to truncation errors when large pressure or momentum changes occur between nearby points (Cheng et al, 1976; Leendertse et al, 1973).

Consequently, an explicit method of integration is used, in which a backward, central or forward difference approximation is substituted for the time derivative. Equations (8) - (12) are thus integrated by a three-time level method in which the forward time-level solution depends upon the solution at the two previous time levels. This method is known as the central-difference, mid-point rule, or leap-frog scheme (Cheng et al, 1976). In the first half of the computation, the finite-difference forms of equations (8), (9), (11) and (12) are used to calculate u, v, ζ and T at time level (n + 1) from the corresponding variables at level (n - 1). The dispersive terms [E] and [F] in the momentum equations and [C] in the mass-balance equations are evaluated from level (n - 1) while the other terms are evaluated from level (n) in order to retain computational stability. The vertical velocities, densities, pressure gradients and stress terms are next computed from the results just obtained for levels (n) and (n + 1). This cycle is repeated as long as required.

This leap-frog scheme has a rigid time-step limitation, beyond which the computation becomes unstable. This is as follows (Grammeltvedt, cited by Leendertse et al, 1973):

$$\Delta t \leq \frac{\Delta x}{\left[2gh_{max}\right]^{\frac{1}{2}}} \tag{23}$$

where h_{max} is the maximum water depth. This time step is a shorter by a factor of about 3.5 than the maximum time step suggested for the ADI method (Williams and Himwood, 1976; Poulton, 1977), but the computational advantages of the leap-frog method outweigh this disadvantage.

For the grid size (360 m) used in most of the Hamilton Harbour modelling described herein, equation (23) indicates a maximum time step of 20s. Computations at this time step, however, were found to be unstable, and a time step of 10s was required for stable computations. This time step was verified by comparing the results of a test computation with those of a similar run using $\Delta t = 6s$; the difference between these time step lengths were negligible. This method of time step validation is identical to that used previously in the 2-dimensional model studies (Poulton, 1977; MOE, 1979). Time steps shorter than the minimum dictated by equation (23) were also used by Leendertse et al (1973, 1975) in their test computations. Several spatial smoothing schemes were also advocated by Harris and Jelesnianski (1964) in order to reduce the extent of numerical instabilities.

MODEL INPUT TO HAMILTON HARBOUR

The model as described in the previous section has been applied to Hamilton Harbour using a grid of space step length 360 m which is 1.5 times the 240 m grid used in the previous 2-dimensional model studies (MOE, 1980). The axes of the two model grids are parallel and the grid points aligned closely so as to allow easy comparisons between the two models run with the same input data. This also allows comparison with the 3-dimensional model run on the 240 m grid; however, at present, the computer costs are too prohibitive to permit use of the 240 m grid on the 3-dimensional model.

The 3-dimensional model grid, together with the real harbour shoreline and the locations of source and sink inputs is shown in Figure 2. The vertical structure of the model grid consists of 3 layers of thicknesses 3, 4 and 9 m, respectively. Water depths are handled by using one, two or three layers per grid square according to the water depth at each point. The number of layers per grid point is shown in Figure 3.

Interactions of the harbour with Lake Ontario (through the Burlington Ship Canal) and Cootes Paradise (through Desjardins Canal), as well as the mouth of Grindstone Creek, have been treated as open boundaries. The model has been programmed to accept current meter data as direct input to the model at real-time intervals of generally 10 min; the purpose of this input is to describe adequately the rapid changes in currents and water quality which occur within minutes at such boundaries as discussed in previous reports on this subject (MOE, 1974, 1977, 1980; Poulton, 1979; Palmer and Poulton 1976). Input from Lake Ontario is entered at the upper two model layers, and from the other open boundaries at the surface layer only. The real-time data input to the model is completed with the specification of hourly wind data as recorded by the Hamilton Harbour Police from a site located at the police docks.

For the calibration attempts described in this section, real-time input data has been used from two periods in which current and water quality meters have been operated: (a) June 29-30, 1974. This is the same period as used in the 2-dimensional model study (Section F); and (b) June 12-14, 1976. For both periods, constant average source and sink flow data were used (Table 1). Wind input for the 1974 period is shown in Figure 4, and for the 1975 period is shown in Figure 5. For both periods, current meter data at the Burlington Ship Canal were read directly into the model at 10-minute intervals for two layers; in addition, for 1976 current meter data from Desjardins Canal were also read directly into the model at 10-minute intervals. Details of the current meter inputs have been described by Kohli (1980) and will not be repeated here. Daily flow records from Grindstone Creek and the average input value from Desjardins Canal (1974 only) were converted to current speeds by dividing by the model grid cross section area (Δx * top layer depth).

MODEL CALIBRATION

The model calibration is conceptually similar to that used with the 2-dimensional model, except that there are more physical parameters to adjust with the 3-dimensional model. Modelled velocity components are compared at 10-minute intervals to current meter data obtained at the internal validation points shown in Figure 2. It should be noted that these metered results are used for calibration purposes only and are not entered into the model calculations. The calculated u and v components were converted into a resultant speed and compass direction, and plotted together with the observed currents as a function of time for the appropriate current meter. Different model grid locations were used in the vicinity of the current meter for the test procedure, and the locations selected represented the best fit to observed data as obtained after summing the differences between observed and modelled velocities for several rows and columns near the validation point.

The physical parameters and their meaning were described in the theoretical section and are summarized here:

Parameter	Meaning
Δt	time step length
Δx	space step (model grid size in horizontal direction)
C	Chezy's coefficient of bottom roughness (eq. 16a and 16b)
C^*	coefficient of wind stress (eq. 15a and 15b)
A_x, A_y	horizontal momentum dispersion coefficients (eq. 8 and 9)
ν_0	Vertical momentum transfer coefficient (eq. 21a and 21b)
ν_1	coefficient of interfacial friction (Prandtl's mixing length) These two coefficients (eq. 19a and 19b) determine the effect of density gradients (Richardson number, presently set to zero), and vertical velocity gradients, on the interfacial shear stress terms $(\tau^{xz})_{k+\frac{1}{2}}$ and $(\tau^{yz})_{k+\frac{1}{2}}$.

Attempts at calibration so far, have included only the hydrodynamic portion of the model, at constant density. Despite the fact that thermal stratification existed during the calibration periods, its effect (reduction of vertical turbulence, corresponding to a decrease in the value of ν_1,) has been ignored at present.

The model time step length was first verified by checking that modelled currents were not a function of time step length, as was previously done with the 2-dimensional model. The model was run for 12 h with the 360 m grid. Input parameters included a wind speed of 6.7 ms^{-1} from WSW, a Chezy coefficient of 200 cm$^{\frac{1}{2}}$ s^{-1}, ν_1 = 5000 cm^2 and time step length Δt = 10 s. The results were compared with a similar run using Δt = 6 s, in order to test the effect of time step length. Figure 6 shows a plot of the modelled u, v, and w components for the first 10 h from point (17, 6,2), which is the mid-depth of a point near harbour station # 270. The time series for the two points are displaced slightly for clarity. The results show that 10 s is an adequately short time for a model grid of this size; consequently this time step was used in further modelling work described here. Three other grid points plotted confirmed this conclusion.

CALIBRATION WITH 1974 INPUT DATA

Work on the 2-dimensional model (Poulton, 1980) and preliminary work on the 3-dimensional model not described here indicated that spin-up time is an important factor that must be accounted for in applying real-time data to the 3-dimensional model, particularly at low initial wind speeds. Under conditions used in the test run for verifying Δt, steady state was approached within the 12 h period, with a rough approximation being achieved within the first few hours. In order to reduce the computer costs of initial model calibration with 1974 real-time input data, it was decided to use the final state from this run as initial conditions for model calibration runs as the wind conditions used were similar to those at the beginning of the 1974 calibration period.

The values of model physical parameters used in runs involving 1974 input data are shown in Table 2, and the location of the current meter used for comparison purposes is given in Figure 2. The initial values of the physical parameters were similar to those used by Leendertse et al (1973) in their test basin. During the comparisons, two layers of grid points were tested.

Although the depth (4 m from surface) of the current meter suggests the use of the top two model layers, simple observation showed that modelled surface currents generally followed the wind direction and not the observed current meter results. Layers 2 and 3 of the grid were therefore tested.

The best agreement found is shown in Figure 7. While the agreement in current direction is reasonable after 4 h, the observed speeds of 5 to 13 cm/s were not simulated, the calculated speeds being fairly constant at 2 to 3 cm/s. Also, this comparison was found in model layer 3, which was at too great a water depth.

For a second calibration attempt (run #2), it was decided that agreement should occur in model layer 2 if possible. Preliminary work had indicated that decreasing the coefficient of interfacial friction ν_1 would result in a large difference between layer 1 and 2 currents, and a smaller difference between layer 2 and 3 currents. It was thus decided to set $\nu_1 = 100$ cm^2; all other parameters were kept unchanged and the model was run for 12 h. The best comparison obtained is given in Figure 8. An initial increase in current speeds was now found for about 7 h. Speeds, however decreased to near zero in the last 5 h. The direction also became more variable, exhibiting a reversal in the last hour which did not occur in the field data.

For another attempt at increasing speeds near the bottom, run #3 was done with the Chezy coefficient C increased to 700 cm$^{\frac{1}{2}}$ s^{-1}. Figure 9 shows the best agreement obtained. This result shows improved agreement compared to runs 1 and 2, and it was felt that a closer approach to model calibration was being achieved.

As the physical parameters used in run #3 were considerably different from those in the spin-up run which output was used for initial conditions, it was decided to repeat the run from initial conditions using the same physical parameters as run #3. The real-time data were then applied after a reasonable spin-up period.

However, the model was found to be unstable when run under these conditions for more that 19 h. For improved stability, the value of ν_1 was increased to 500 cm$^{\frac{1}{2}}$ s^{-1} and the model run for 24 h from rest. This run (run #4) was stable but failed to reach steady state at 24 h. As the effect of spin-up time of the order of 12 to 24 h was found to be significant with the 2-dimensional model in

Toronto Harbour (Poulton, 1980), it was decided to test this effect using two parallel runs (4A and 4B), done with spin-up times of 12 and 20 h, respectively. Figures 10 and 11 show the best comparison with observed data that was obtained (using the same model grid point in each case). Run #4B (Figure 11) lost stability at 18.8 h, indicating complete stability still did not exist. In addition, the direct comparison between the two figures shows that the results are significantly different, and in only fair agreement with observed data. Clearly the model is not producing meaningful results under the conditions used in these runs; the agreement in the earlier run (#3; Figure 9) under similar conditions was somewhat fortuitous.

In an attempt to improve stability, ν_1 was further increased to 1000 cm^2. This run (run #5) still became unstable; comparisons with observed data were similar to runs #4A and 4B and are not shown.

In these unstable model runs, the modelled currents show large spatial variations in direction, frequently between neighboring grid points. An example is shown for layer 1, run #4B, in Figure 12. It was suspected that increasingly large differences between adjacent velocity components contributed to instability and changes were needed to smooth out these variations. For this reason, the horizontal momentum dispersion coefficients A_x and A_y were increased to 1×10^4 cm^2 s^{-1} and the model run for 24 h with real-time input from the run #5 spin-up condition. This run (#5A) was stable for 24 h. However, no improvement was obtained in comparisions with observed results. At this point it was decided to attempt calibrations with a completely different set of input and validation data.

CALIBRATION WITH 1976 INPUT DATA

An input data set from June 1976 was selected, which was characterized by winds from the northeast for at least a portion of the record. The physical parameters affecting calibration were set to the same values as the last run with 1974 data (which produced stability but not a good comparison with observed results). They were: $C = 700\ \mathrm{cm}^{\frac{1}{2}}\ \mathrm{s}^{-1}$, $\nu_1 = 1000\ \mathrm{cm}^2$, $A_h = 10^4\ \mathrm{cm}^2\mathrm{s}^{-1}$. The wind input for 12 hours preceding the model run plus 48 hours of modelled time is shown in Figure 5. The location of the current meter data used for comparison is shown in Figure 1. The model was spun up for 24 h with wind from the northeast at 5.3 ms^{-1} and then run for 48 h with real-time data as already described.

Comparisons with metered data are shown in Figure 13 for two locations in layer 2. This layer was selected for comparison as the current meter was located at 6 m depth. At both locations, the modelled direction was incorrect for the first 6 h. A fairly close correspondence between observed and modelled speeds and directions was observed for the remainder of the first 24 h, although the variation of model speeds at location (16, 11, 2) (Figure 13a) with time was inconsistent with the observed variation. For most of the second 24 h, modelled directions were almost opposite those observed, and modelled speeds were consistently much too low (Figures 13c-d). Only during the last 8 h at location (18, 12, 2) and the last 4 h at location (16, 11, 2) did the modelled directions approach the observed directions. Other locations within the same model layer yielded worse results; as with comparisons involving 1974 input data, the illustrated locations represented the best agreements between observed and modelled data obtained by testing all grid points within several grid squares of the meter location (Figure 2). Obviously the model in the present condition was not able to simulate the observed current speeds and direction changes during the last 24 h. Further attempts at model calibration, by altering the values of physical parameters, were discontinued at this time.

Despite the lack of agreement between observed and modelled currents over much of this time interval, it was felt useful to present a series of vector plots of modelled currents to show the predicted changes with time as the wind direction (Figure 5) shifts from NE to SW. These plots are shown in Figures 14a-e. At zero time (i.e.

after 24 h of spin-up with NE winds), surface currents were mainly from east to west, showing a deflection to the right of the wind direction as predicted by the Coriolis effect. Some return flow can be found in the deepest part of the west end of the harbour. Mid-depth currents in the deepest part of the harbour are deflected farther to the right of the wind direction, and form a counter-clockwise circulation at the west end of the harbour. As expected, bottom currents return against the wind.

Their speed (see plotting scales on figures) is considerably lower than those of the upper two layers; surface currents are the fastest. Twelve hours later (Figure 14b), very little change in modelled currents has occurred, as expected due to the constant wind direction (Figure 5).

After 24 hours, the wind direction had begun to shift. Currents (Figure 14c) were much slower in the top two layers, although directions had not yet changed much. Bottom layer speeds and directions had not begun to change appreciably.

After 36 hours, winds were from the SW (Figure 5) and surface currents (Figure 14d) had shifted around to follow the winds. Mid-layer currents in the deepest zone were again shifted to the right of surface currents, and bottom layer currents were in the opposite direction. These layers again both exhibited lower speeds than surface currents, especially in the middle layer at the west end and southeast corner of the harbour. Six hours later (Figure 14e), under SW to W winds, the currents in all layers had shifted farther to the right; mid-depth and bottom currents were faster while surface currents were approximately of the same magnitude. Although not quantitatively verified, these results do indicate in a qualititative manner the response of the harbour currents to shifts in wind speed and direction. Similar observed variations of current speed and direction between depths representative of the upper two model layers have been observed during drogue trackings carried out during the summer of 1979 in the east end of the harbour (Figure 15).

The fact that modelled mid-layer currents are frequently opposite in direction to observed currents suggests that bottom layer current directions may agree with the observed direction for portions of the time. Figure 16 shows a test of this hypothesis. It is seen that during the first 6 hours and from 32 to 40 h modelled time the current directions are indeed reasonably close to the observed direction, although modelled speeds are considerably lower than observed speeds. Between 40 and 48 h modelled time, results from either the mid-depth or bottom layer approach the observed conditions. This result suggests that because of the known harbour vertical instability, water flowing past the fixed current meter locations may be representative of different model layers at different times. Confirmation of this suggestion would require more vertical layers in the model and correspondingly increased computer costs.

DISCUSSION

The results described in this section illustrate that calibration of a 3-dimensional model is a very complicated process. Some of the model coefficients were determined from literature surveys or from the prior work of Leendertse et al (1973, 1975) with the same model. These served to establish a range of values within which a realistic approach to calibration might be achieved. Additional refinement of the variables is exceedingly difficult and complicated; moreover, it requires an adequate field data base including currents from several depths in the harbour which were not available in this study. Rasmussen and Badr (1979) have applied mathematical optimization techniques including least-squares methods and mini-max criterion to the 2-dimensional Hamilton Harbour model. Although they report reasonable success, they restricted their effort to a 12 h period in real-time; results could change as the time interval is extended. Furthermore, application of their systematic method to the 3-dimensional model with its larger number of coefficients, becomes a far more cumbersome and time-consuming process.

The greatest shortcoming in the present work, as illustrated by the run with 1976 data, is the limited extent of vertical resolution in the model. Results of drogue trackings in the harbour during 1979 (Figure 15) show that although currents very close to the surface are quite close to wind directions, currents within 6 m of the surface are considerably slower as well as in different directions. Aditional field data of this nature plus additional model layers are required to describe the vertical dependence of currents and provide a proper value for the coefficient of internal friction ν_1. This parameter is the one which has the greatest effect on determining the depth dependence of modelled currents and without a realistic value of ν_1, one cannot reasonably adjust coefficients like C and θ. It is thus seen that adequate vertical discretization of the model plus sufficient validation data as a function of depth are important for proper calibration of the model.

On the other hand, the method of model-meter comparison as used here should be considered a very severe test of model validity. This is true despite the fact that the same method was used with better success in the 2-dimensional Toronto Harbour model. Simons (1974) used similar plots of observed vs. computed currents for his Lake Ontario model, but in addition, used vector plots of 3-day mean currents. Lam and Halfon (1978) used monthly mean currents measured at several locations in Lake Superior to calibrate their 3-dimensional hydrodynamic model; results confirmed the general circulation pattern but frequently underestimated the speed of nearshore currents. They attributed this shortcoming to the lack of nearshore grid resolution. In the same paper, they were able to apply the hydrodynamic model successfully to a two-compartment phosphorus model. In other words, it may not be necessary to obtain an accurate prediction of currents at short time scales; estimates of the average harbour circulation pattern may be sufficient.

FUTURE MODELLING WORK

The purpose of numerical modelling in Ontario is to formulate discharge requirements which will ensure that the quality of receiving waters meets the criteria established by the Ministry of the Environment (Blue Book). Where local violations of the criteria occur adjacent to the discharges, models can be used to define the limits of limited use zones (mixing zones or zones of non-compliance) as defined by the International Joint Commission. Valid attempts at environmental assessment require a properly calibrated and verified model; moreover, they require an intelligent choice of the proper model to fit the problem at hand. Although the 2-dimensional model of Hamilton Harbour (Section F) has only limited usefulness under conditions of thermal stratification, it proved considerably more successful when applied to Toronto Harbour (Poulton, 1977, 1979, 1980). Either type of model is useful for describing only short-term events such as storm runoffs or accidental discharges and is of no use in describing longer-term (e.g. seasonal) phenomena.

The present work has emphasized the need for adequate vertical discretization of the model plus sufficient validation data as a function of depth. Further model calibration should be done only with such data available. The following requirements are suggested:

1. A minimum of 5 model layers are required, including 3 layers at the Burlington Ship Canal.

2. Vertical strings of current meters including temperature should be operated in the harbour for validation data, including at least three different depths. Open boundary data are also required for 3 depths in the Burlington Ship Canal.

3. Wind data are required from a recording anemometer located over the water surface and operating at a 10-minute or shorter interval.

4. Air and sediment temperature data are required plus a measure of solar radiation as a function of time for a realistic temperature calibration.

In addition to these requirements, extension of the model to include turbulent energy computations might be helpful. Leendertse and Liu (1977) have produced an extension of the 3-dimensional model including sub-grid scale turbulent energy calculations from which vertical mass and momentum exchange coefficients are computed. Horizontal momentum exchange calculations are also improved by computing these as a function of local velocity deformations calculated in the finite difference grid. Computational stability was also improved by introducing an implicit method for calculating the vertical exchange terms. Applied to Hamilton Harbour, this should ease the stability problems observed during computations with runs #4 and #5 as earlier discussed. The computer program for these calculations is now available (Leendertse and Nelson, 1977) and need only be adopted to the present Hamilton Harbour situation. Before these calculations are implemented, however, the value of the extra effort which would be required in implementing these calculations should be carefully assessed.

Any continued modelling program as outlined above naturally represents an ambitious and expensive undertaking. Obviously, the benefits of such prediction capabilities must be carefully assessed before a commitment is undertaken. It would also be hoped that the developed model could be extended to other areas of concern in Ontario such as Toronto Harbour or the Bay of Quinte with minimum additional effort once the model has been validated in Hamilton Harbour. It is suggested that the model be let out to an external contractor such as a university where it could form a profitable Ph.D. or post-doctoral program as well as utilization of more economical computer facilities. In addition, valuable cooperation between the Ministry and the outside agency would be established or continued, particularly in the execution of the field program as elaborated above.

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TABLE 1

SOURCE AND SINK DATA USED FOR NUMERICAL MODEL
HAMILTON HARBOUR, JUNE-JULY 1974

MAP I.D.	Outfall or Intake	Flow (m^3s^{-1})
A	Hamilton WPCP	3.68
B	Ottawa St. Slip*	14.06
C D	(Stelco Intake #2) less (Stelco S. Open Cut Sewer)	-12.2
E	Stelco N. Trunk Sewer	3.04
F	Stelco Intake #1	-2.40
G	Stelco #3 Open Hearth Sewer	2.40
H	Stelco 148" Plate Mill	0.94
I	Dofasco raw water intake	-8.9
J	Dofasco (coke overn by-products), boiler house discharge, silicon steel)	2.74
K	Skyway WPCP	0.68
L	Desjardins Canal	0.066**
M	Grindstone Creek	0.64 **

Note:

Negative flows are intakes (concentrations not required).

* Includes: Stelco (E. side lagoon, HCl regenerator and cold mill, hot strip mill, heavy gauge shear line), Dofasco (lagoon, Ottawa St. sewer) and CIL (total plant less service water intake).

** These points were treated as open boundaries. Flow data for Desjardins Canal (1974 only) and for Grindstone Creek were converted to the corresponding current speeds in cm/s by dividing by the cross-section area of the one-layer open boundary (3m x 360 m). In 1976, current meter data were used for Desjardins Canal.

TABLE 2

VALUES OF PHYSICAL PARAMETERS USED IN REAL TIME 3-d MODEL RUNS USING JUNE 1974 INPUT DATA

Run #	Spin-Up Time, h	Model Run Time, h	Chezy Coefficient C $cm^{1/2}\ s^{-1}$	Interfacial Friction ν_1 cm^2	Momentum Dispersion A_x, A_y $cm^2\ s^{-1}$
1	12	12	300	5000	500
2	12	12	300	100	500
3	12	12	700	100	500
4A	12	24	700	500	500
4B	20	18.8*	700	500	500
5	24	20*	700	1000	500
5A	24	24	700	1000	10000

Note: All runs used C* (wind stress coeff.) = 0.020

ν_o (vertical momentum transfer coeff. = $0.0148\ cm^2\ s^{-1}$

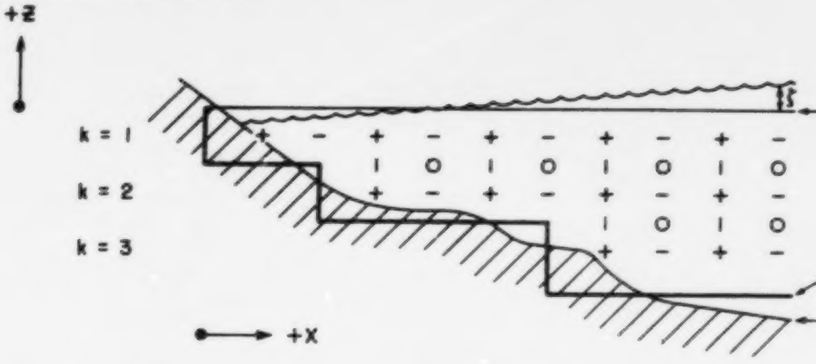
* Run blew up at stated time.

Runs 1, 2 and 3 were done from Run 1 spin-up conditions.

Runs 4A and B were done from Run 4 spin-up conditions.

Runs 5 and 5A were done from Run 5 spin-up conditions.

(a) VERTICAL (X-Z PLANE)



EQUILIBRIUM WATER SURFACE.

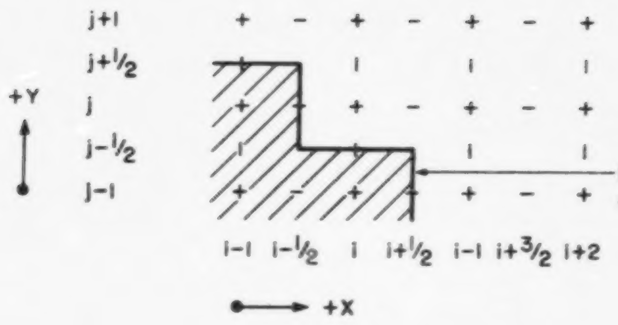
DENOTES THE LIMIT OF THE MODELLED AREA.

HYPOTHETICAL ACTUAL SEDIMENT-WATER INTERFACE.

LEGEND

+	LOCATION OF COMPUTATIONS FOR CONCENTRATION, TEMPERATURE AND V-VELOCITY BETWEEN ROWS.
−	LOCATION OF COMPUTATIONS FOR U-VELOCITY.
I	LOCATION OF COMPUTATIONS FOR W-VELOCITY.
O	LOCATION FOR INTERFACIAL STRESS FORMS $\tau^{XZ}_{K-1/2}$ AND $\tau^{XZ}_{K+1/2}$

(b) HORIZONTAL



DENOTES THE LOCATION OF A HYPOTHETICAL CLOSED BOUNDARY.

LEGEND

−	LOCATION OF COMPUTATIONS FOR U-VELOCITY.
I	LOCATION OF COMPUTATIONS FOR V-VELOCITY.
+	LOCATION OF COMPUTATIONS FOR OTHER PARAMETERS (WITHIN LAYER FOR INTEGER k; AT LAYER BOUNDARY FOR HALF-INTEGER k).

FIGURE 1 - 3-D MODEL GRID REPRESENTATIONS

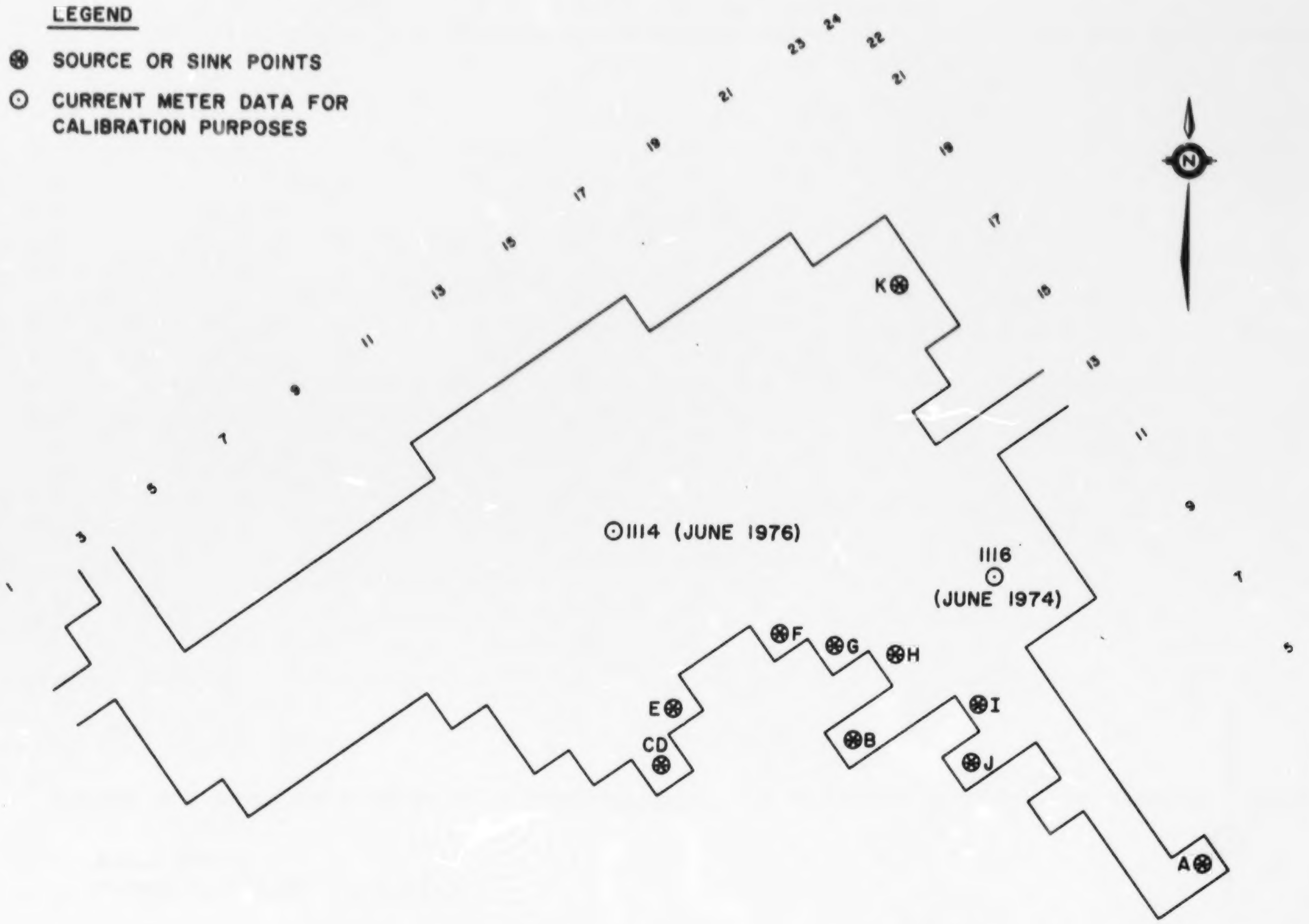

LEGEND
⊛ SOURCE OR SINK POINTS
⊙ CURRENT METER DATA FOR CALIBRATION PURPOSES
N
1
3
5
7
9
11
13
15
17
19
21
23
24
22
21
19
17
15
13
11
9
7
5
K
⊙1114 (JUNE 1976)
1116
(JUNE 1974)
F
G
H
E
CD
B
I
J
A

FIGURE 2 - HAMILTON HARBOUR 3-DIMENSIONAL MODEL GRID, SPACE STEP SIZE 360 m SHOWING LOCATIONS OF SOURCE INPUT DATA AND VALIDATION CURRENT METERS

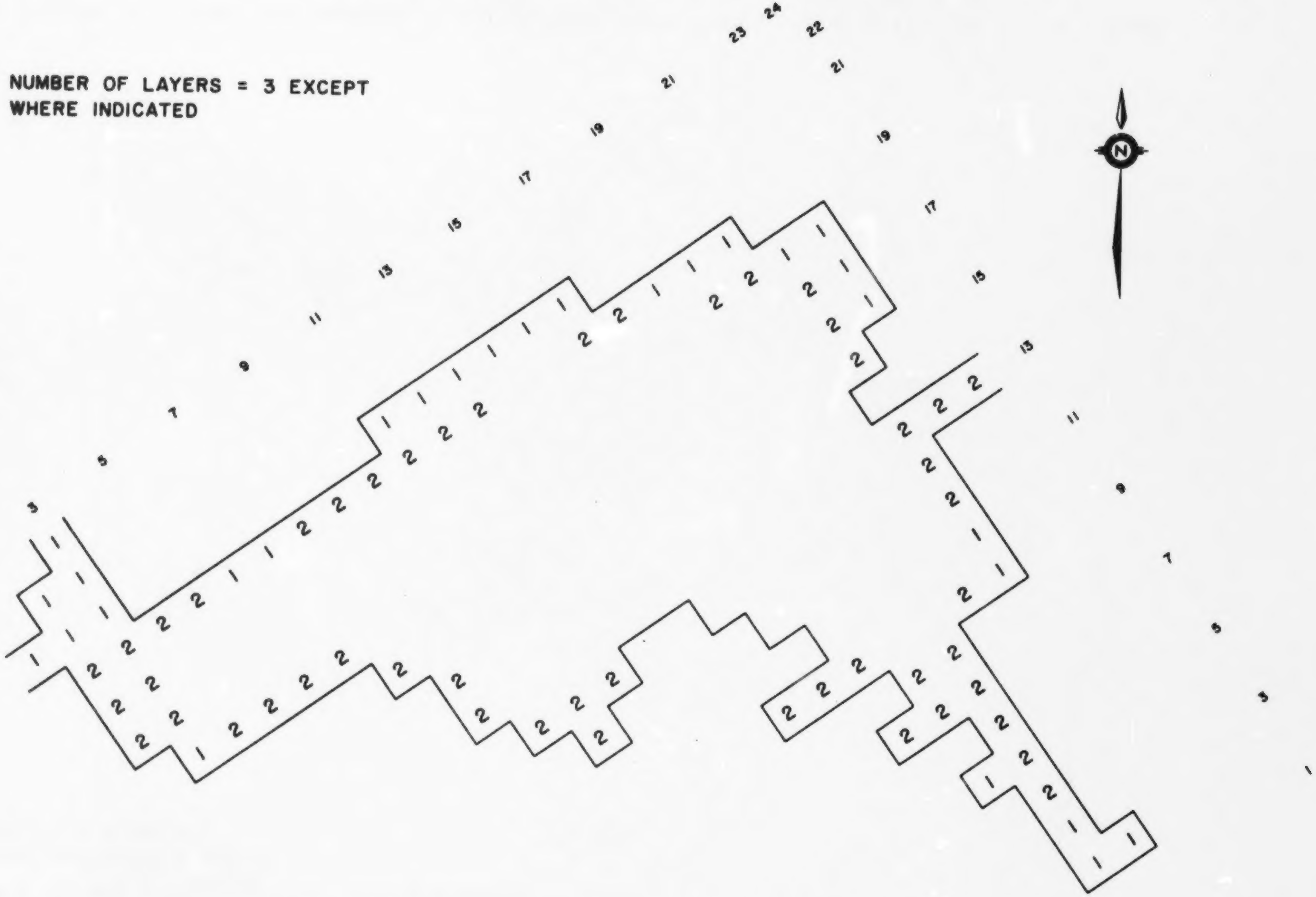

NUMBER OF LAYERS = 3 EXCEPT
WHERE INDICATED
N

FIGURE 3 - HAMILTON HARBOUR 3-DIMENSIONAL MODEL GRID, SPACE STEP SIZE 360 m SHOWING NUMBER OF DEPTH LAYERS FOR EACH GRID SQUARE

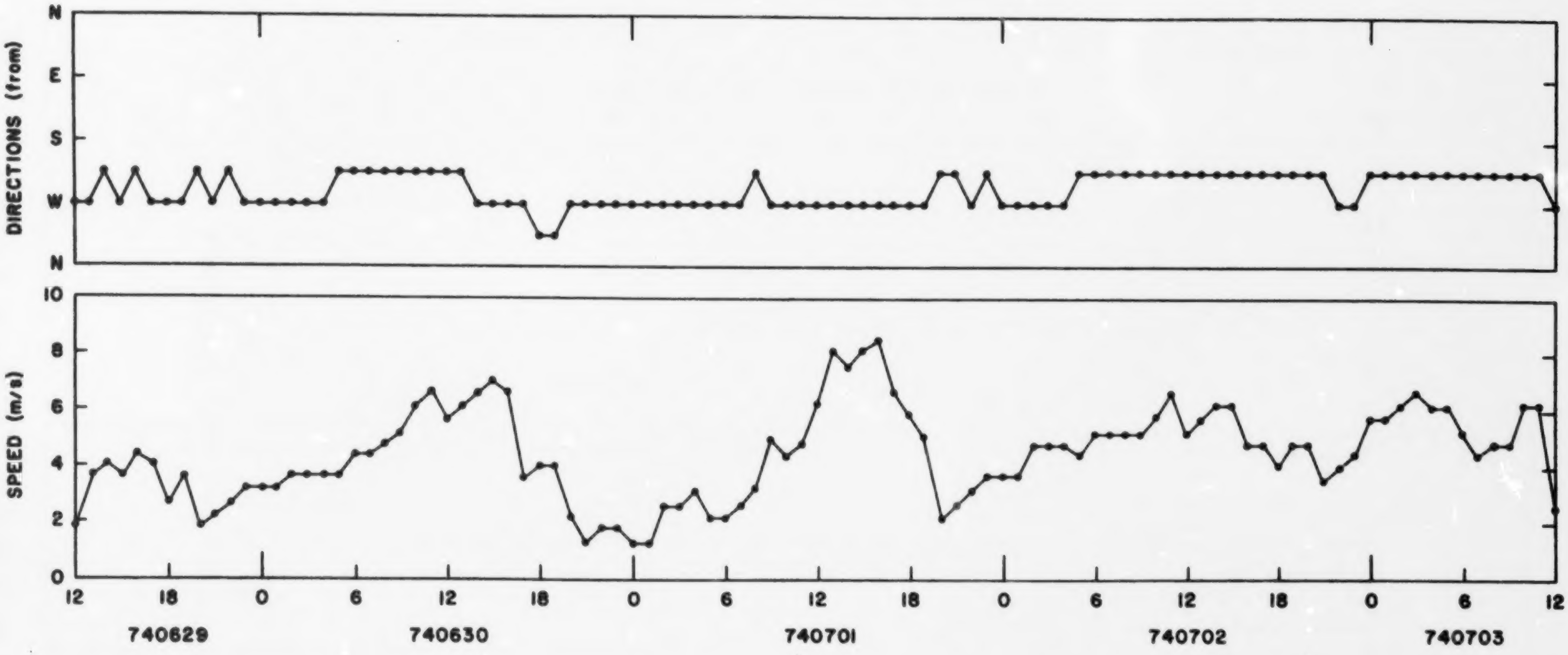


FIGURE 4 - WIND DATA INPUT TO NUMERICAL MODEL, AS RECORDED BY HAMILTON HARBOUR POLICE, 1974

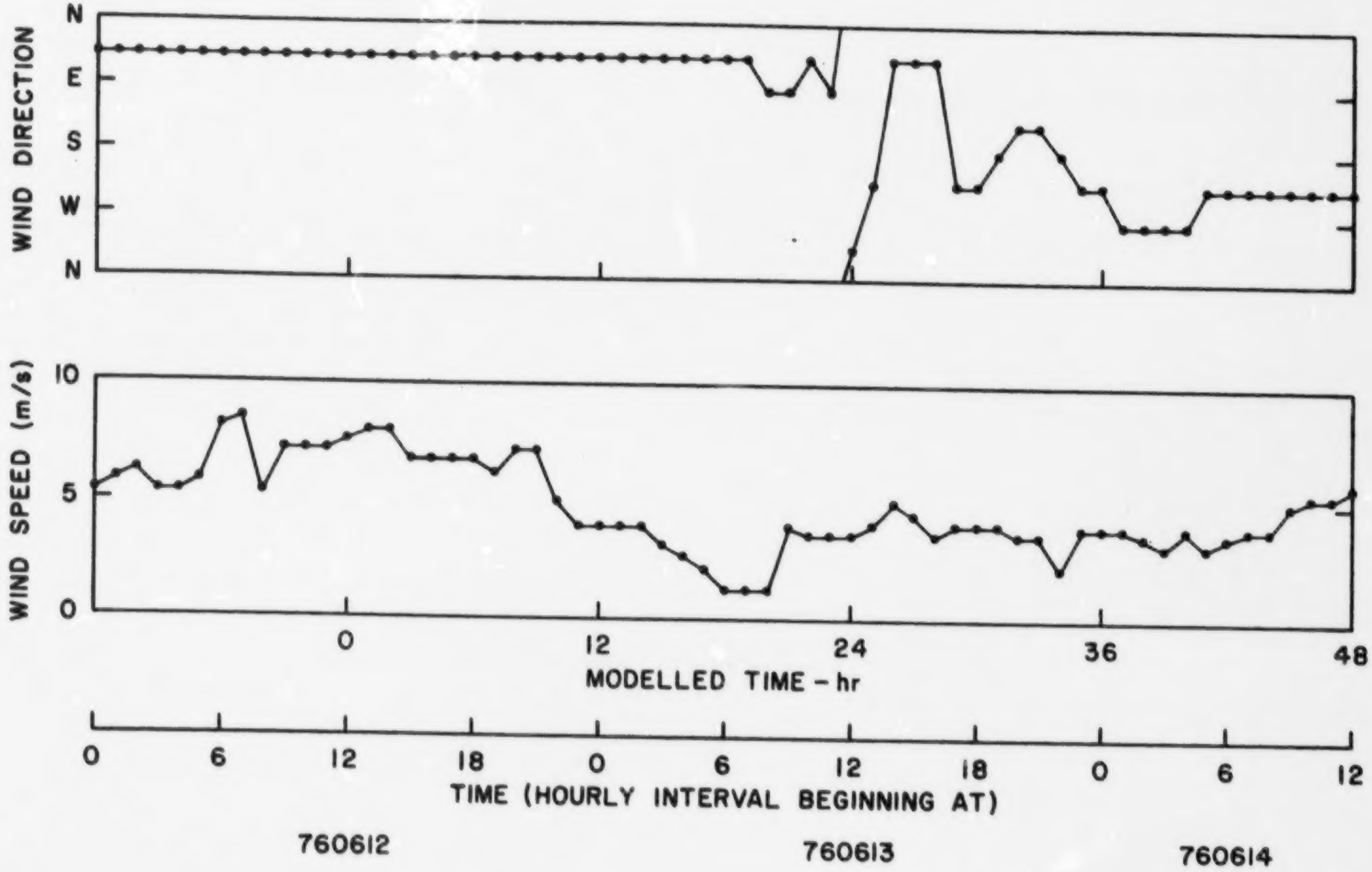


FIGURE 5 - HOURLY WIND INPUT DATA TO 3-DIMENSIONAL NUMERICAL MODEL AS RECORDED BY HAMILTON MARINE POLICE, 1976

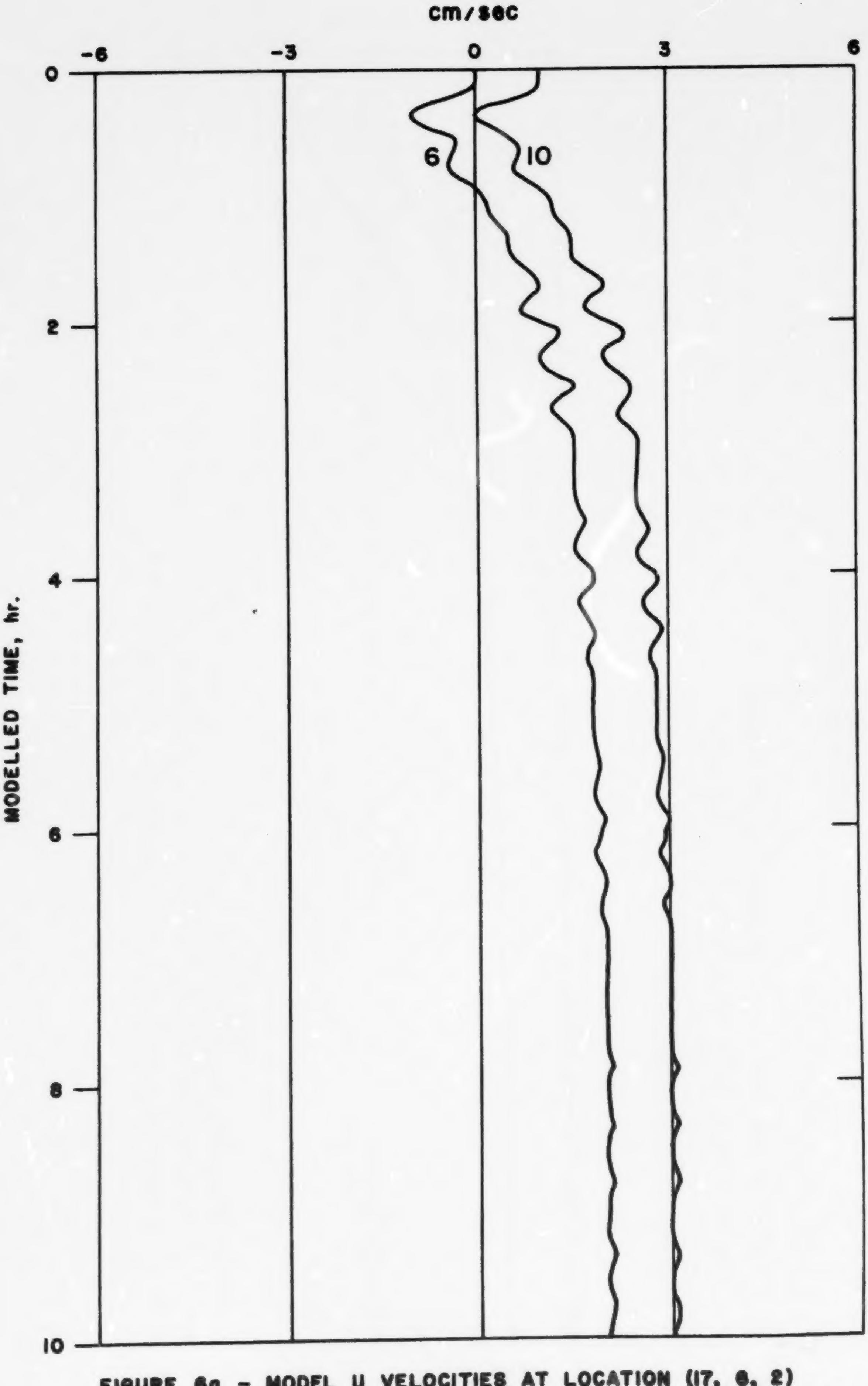


FIGURE 6a – MODEL U VELOCITIES AT LOCATION (17, 8, 2) COMPARISON OF RESULTS FOR ΔT = 6 AND 10 sec.

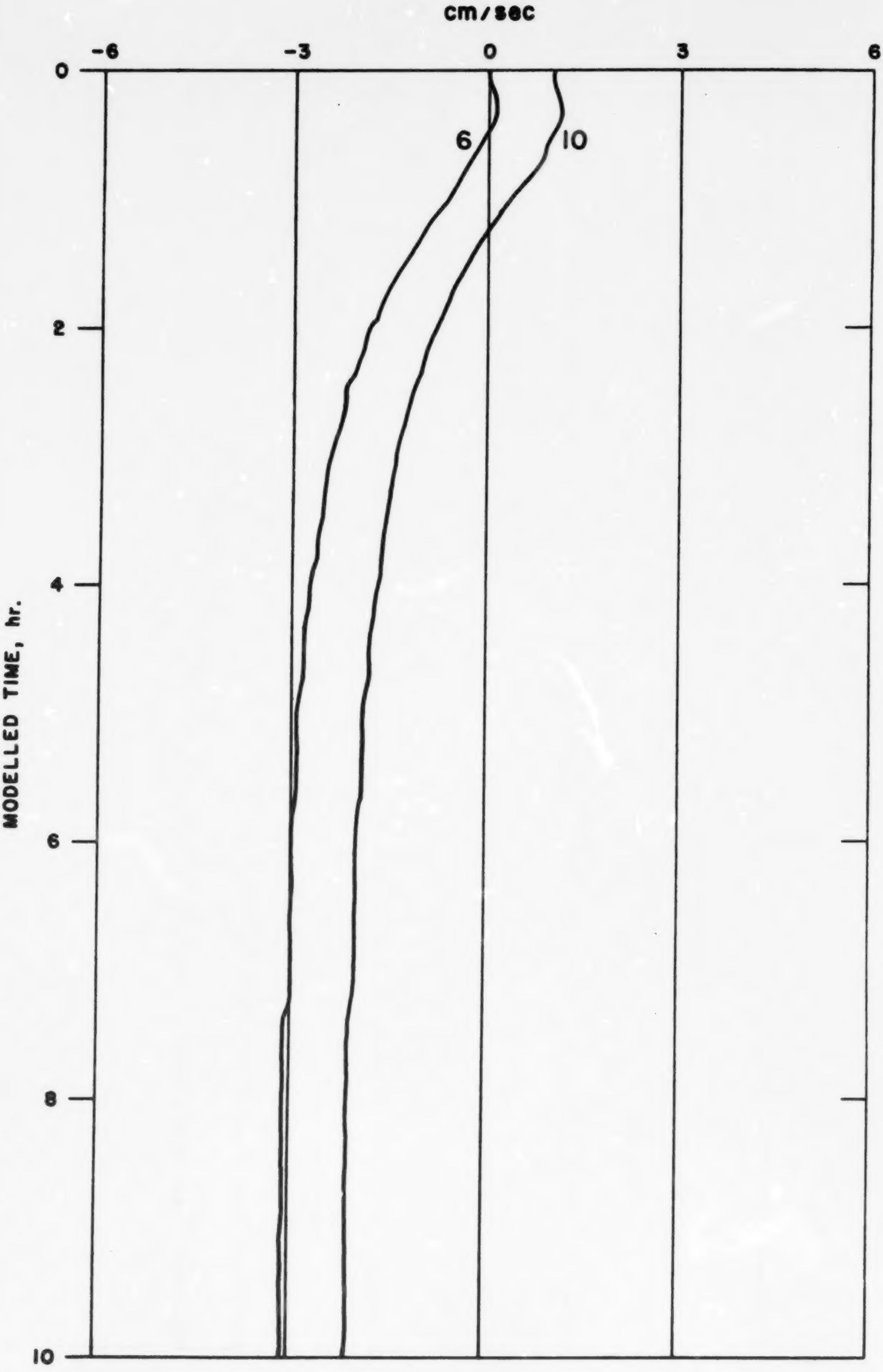


FIGURE 6b - MODEL V VELOCITIES AT LOCATION (17, 6, 2)
COMPARISON OF RESULTS FOR ΔT = 6 AND 10 sec.

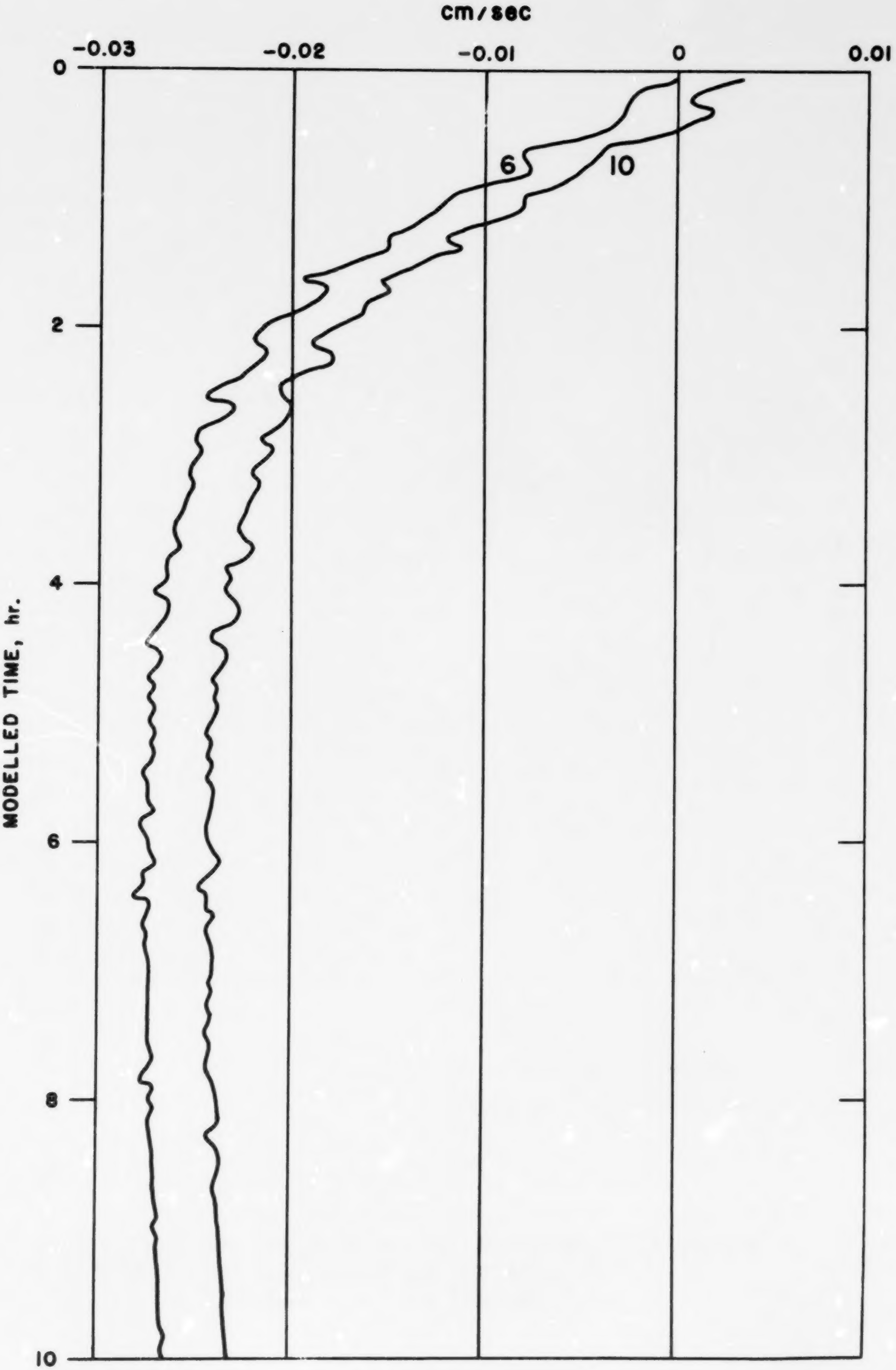


FIGURE 6c - MODEL W VELOCITIES AT LOCATION (17, 6, 2)
COMPARISON OF RESULTS FOR ΔT = 6 AND 10 sec.

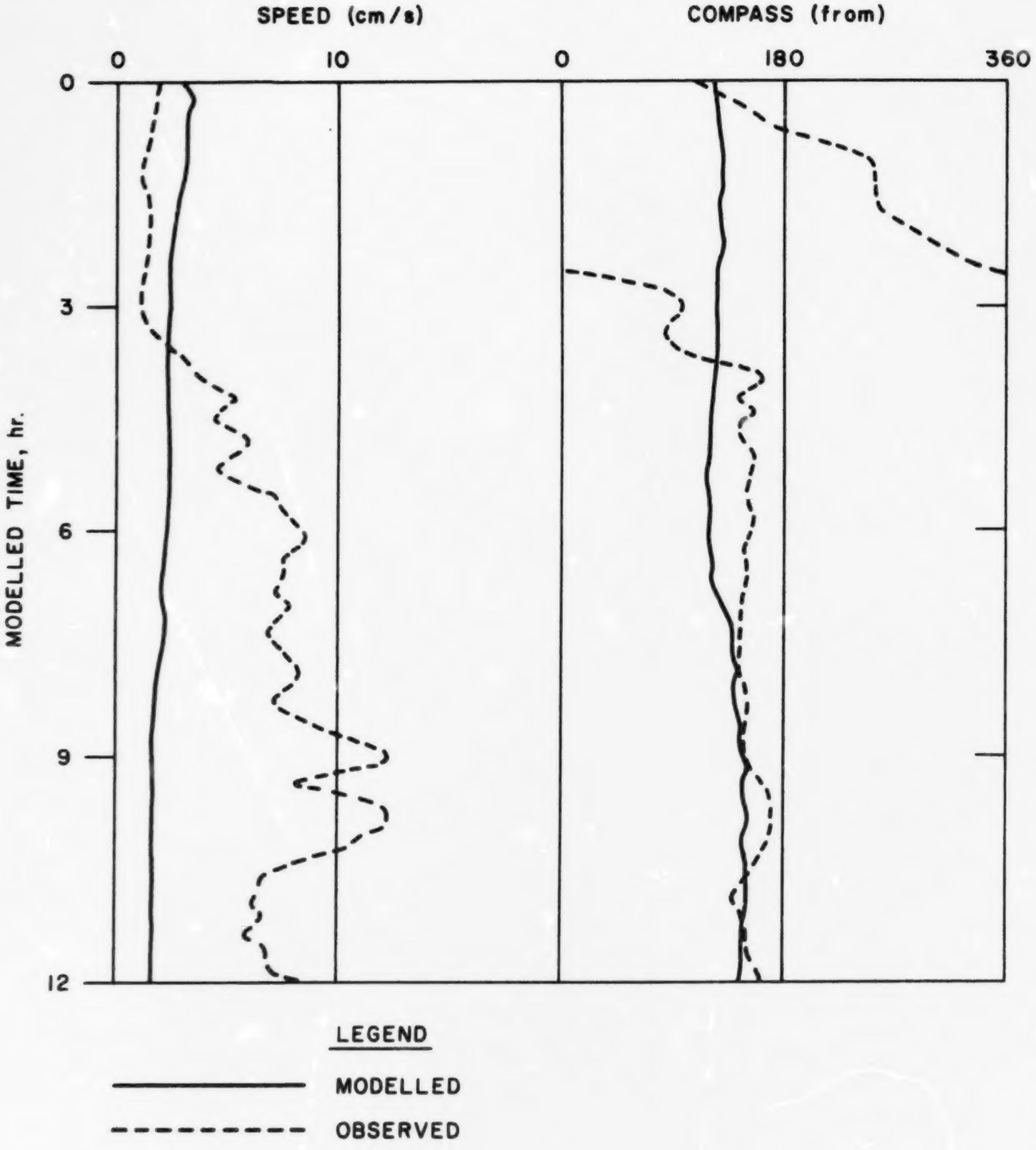


FIGURE 7 - COMPARISON OF OBSERVED AND MODELLED VELOCITIES AT LOCATION (11, 19, 3), JUNE 1974 RUN N° 1 ($C = 300\ \mathrm{cm}^2\ \mathrm{s}^{-1}$, $\nu_1 = 5000\ \mathrm{cm}^2$)

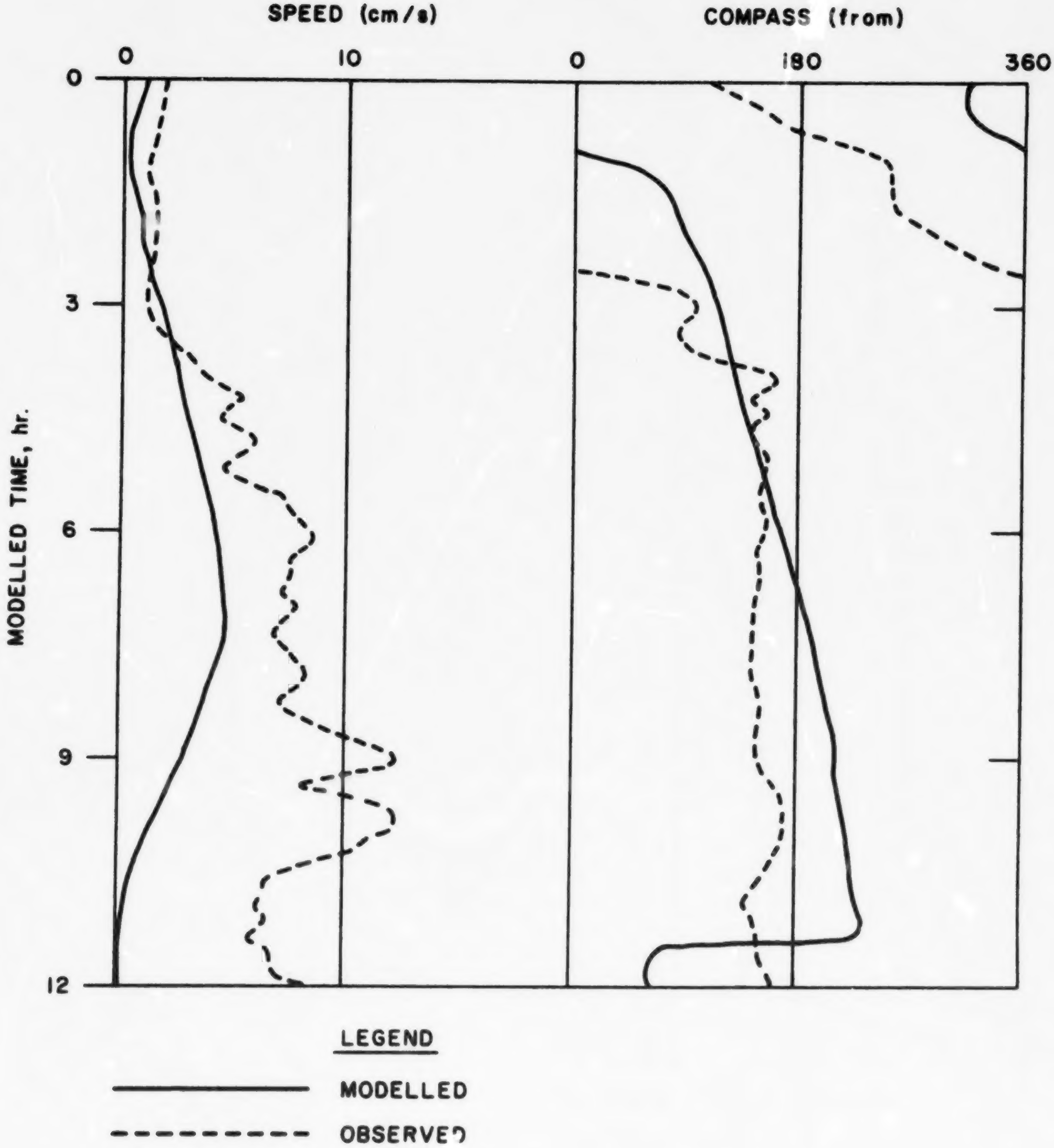


FIGURE 8 - COMPARISON OF OBSERVED AND MODELLED VELOCITIES AT LOCATION (11, 18, 2), JUNE 1974 RUN N° 2 ($C = 300 \text{ cm}^2 \text{ s}^{-1}$, $\nu_1 = 100 \text{ cm}^2$)

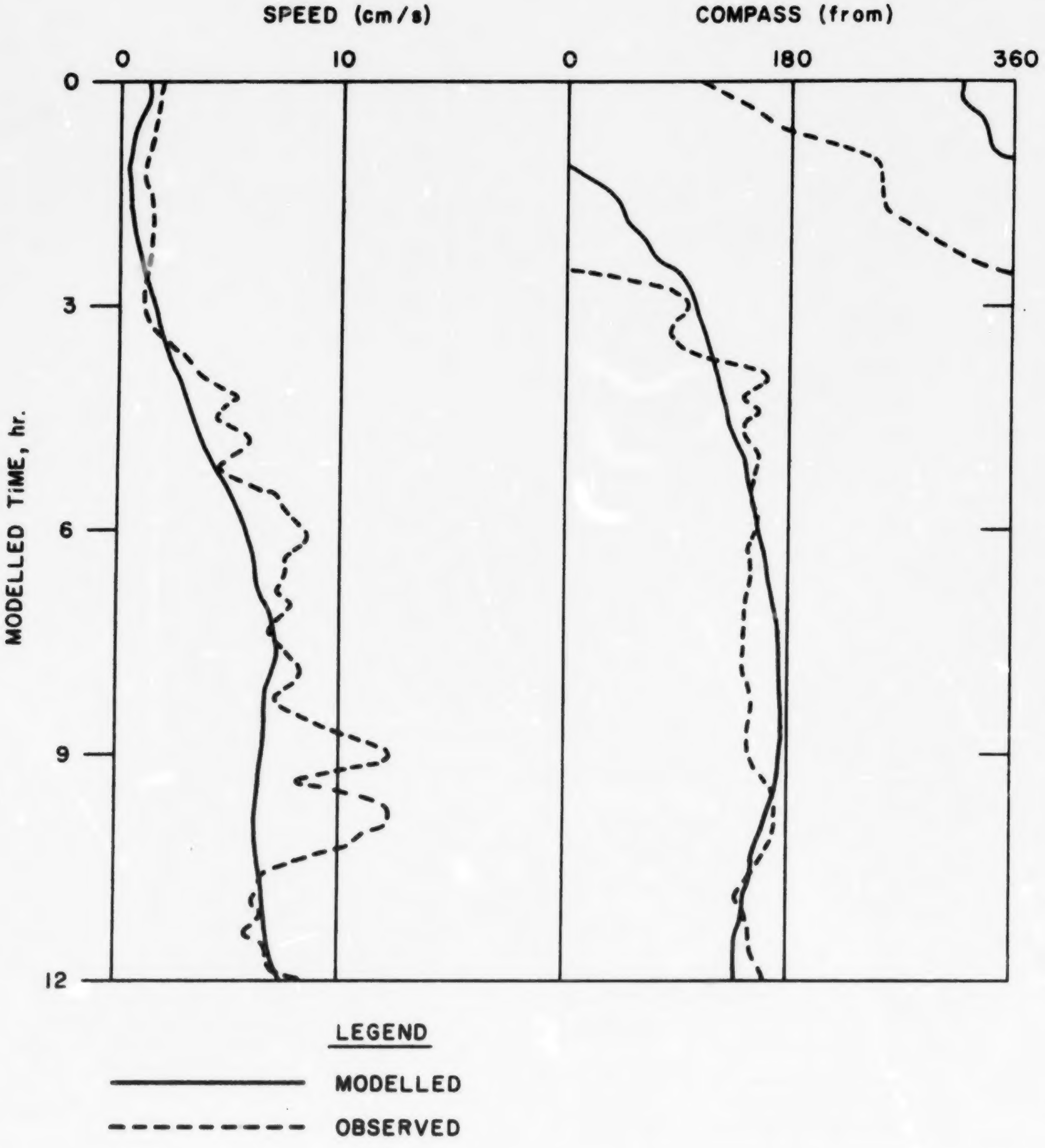


FIGURE 9 - COMPARISON OF OBSERVED AND MODELLED VELOCITIES AT LOCATION U (11, 18, 2), V (10, 18, 2), JUNE 1974 RUN Nº 3, ($C = 700 \text{ cm}^2 \text{ s}^{-1}$, $\nu_1 = 100 \text{ cm}^2$)

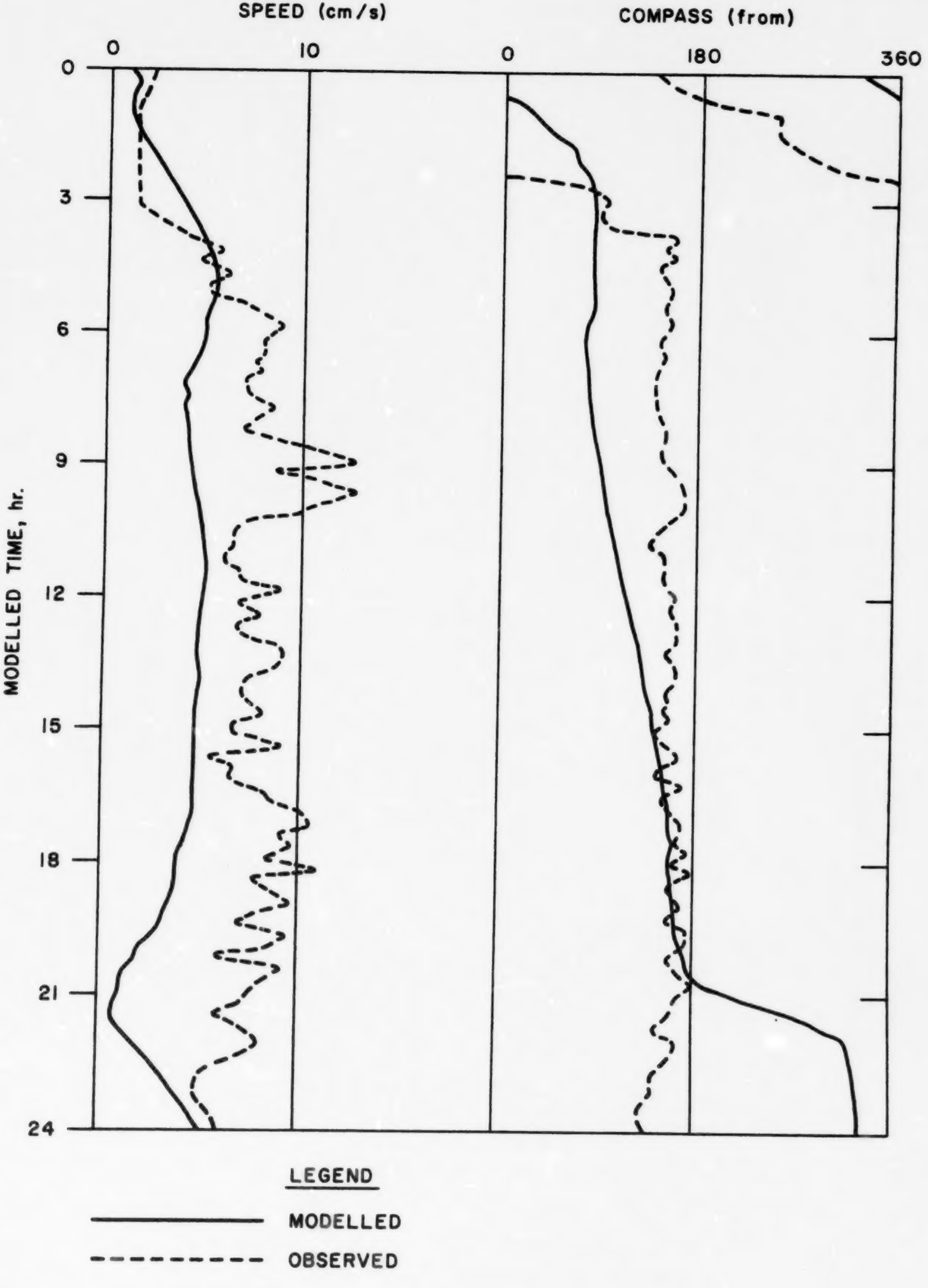


FIGURE 10 - COMPARISON OF OBSERVED AND MODELLED VELOCITIES AT LOCATION (10, 19, 2), JUNE 1974 RUN Nº 4A ($C = 700\ cm^2\ s^{-1}$, $\nu_1 = 500\ cm^2$)

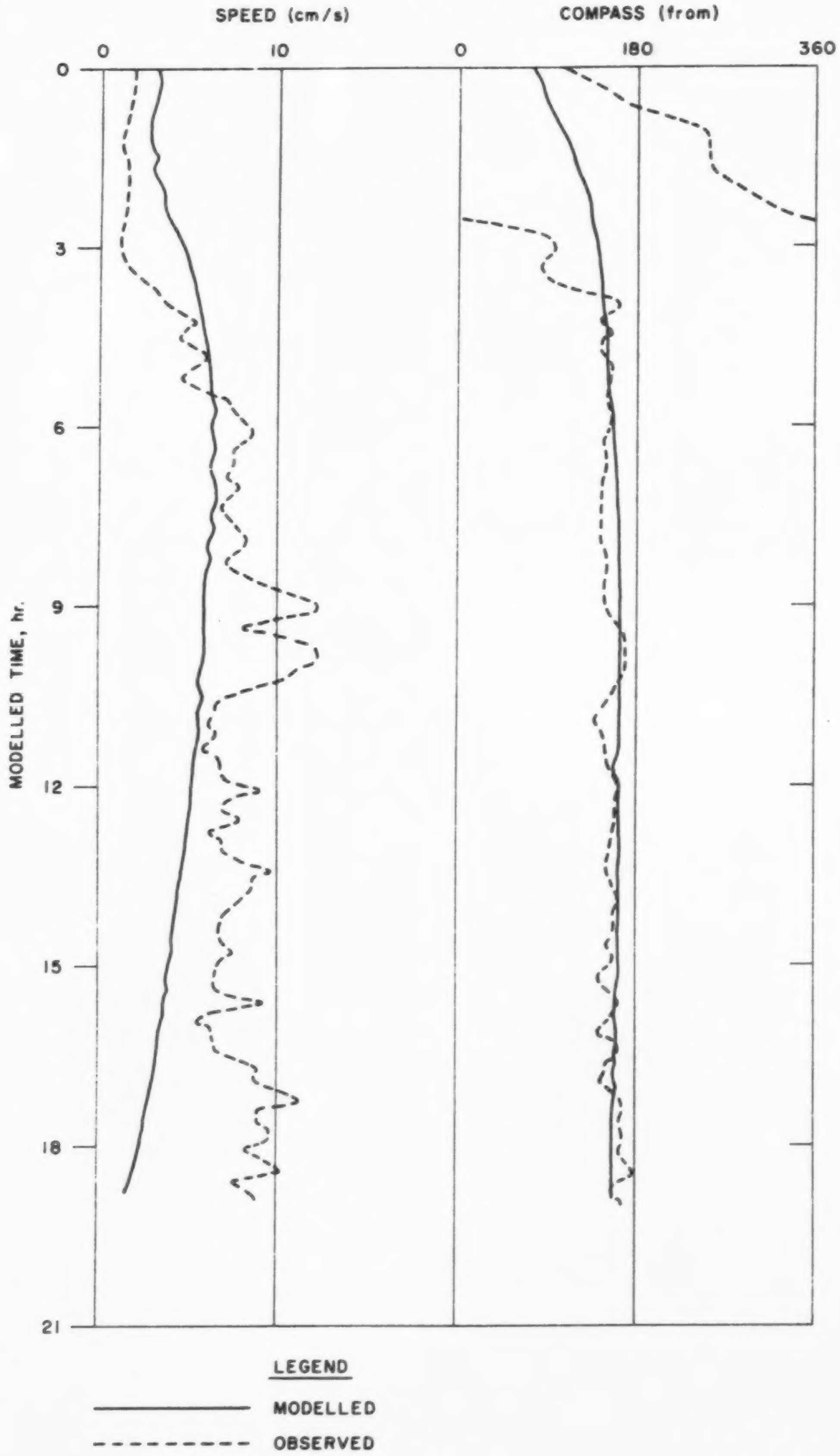


FIGURE 11 - COMPARISON OF OBSERVED AND MODELLED VELOCITIES AT LOCATION (10, 19, 2), JUNE 1974 RUN Nº 4B ($C = 700$ cm^2 s^{-1}, $\nu_1 = 500$ cm^2, SPINUP TIME 20 hr)

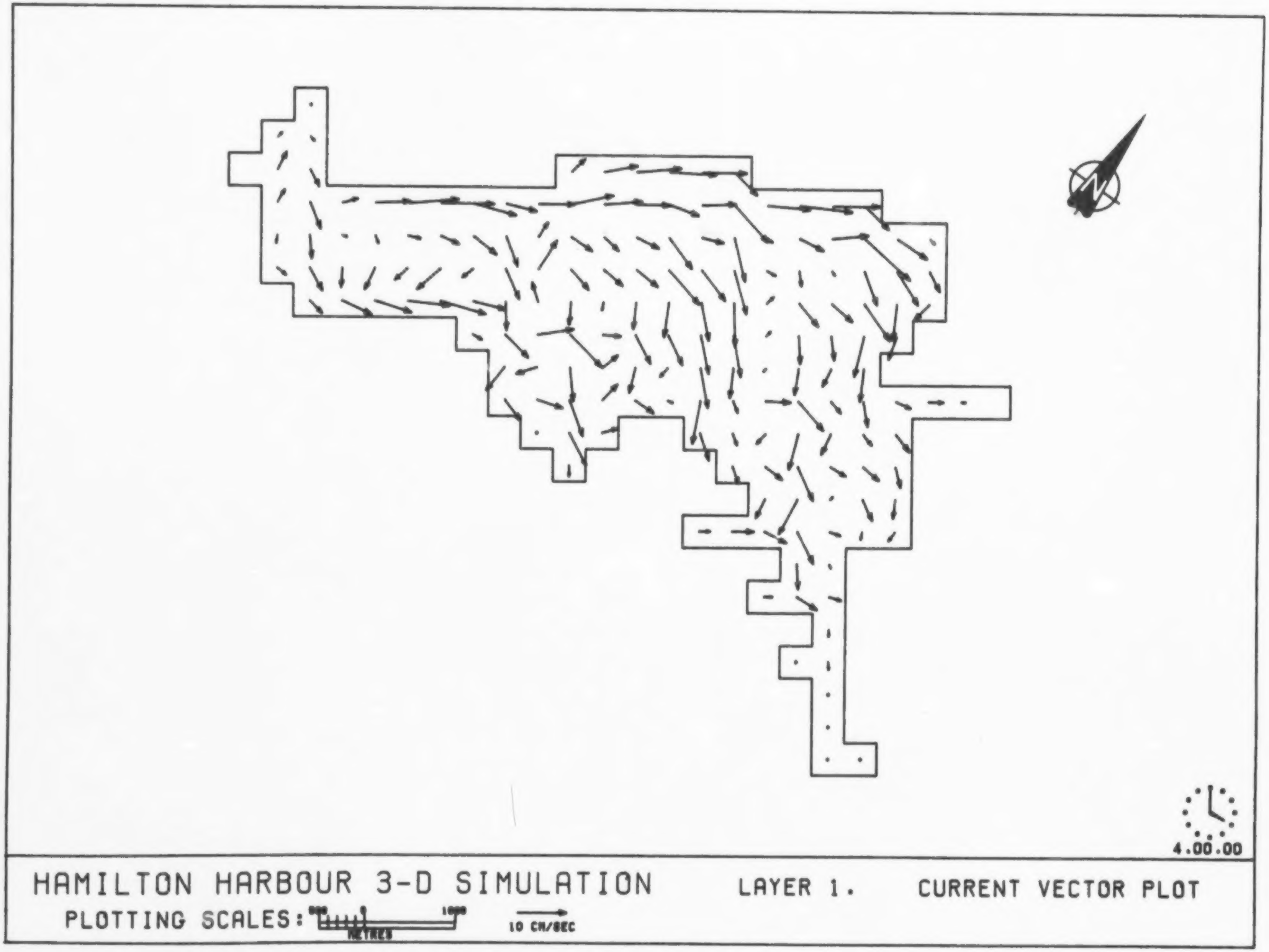
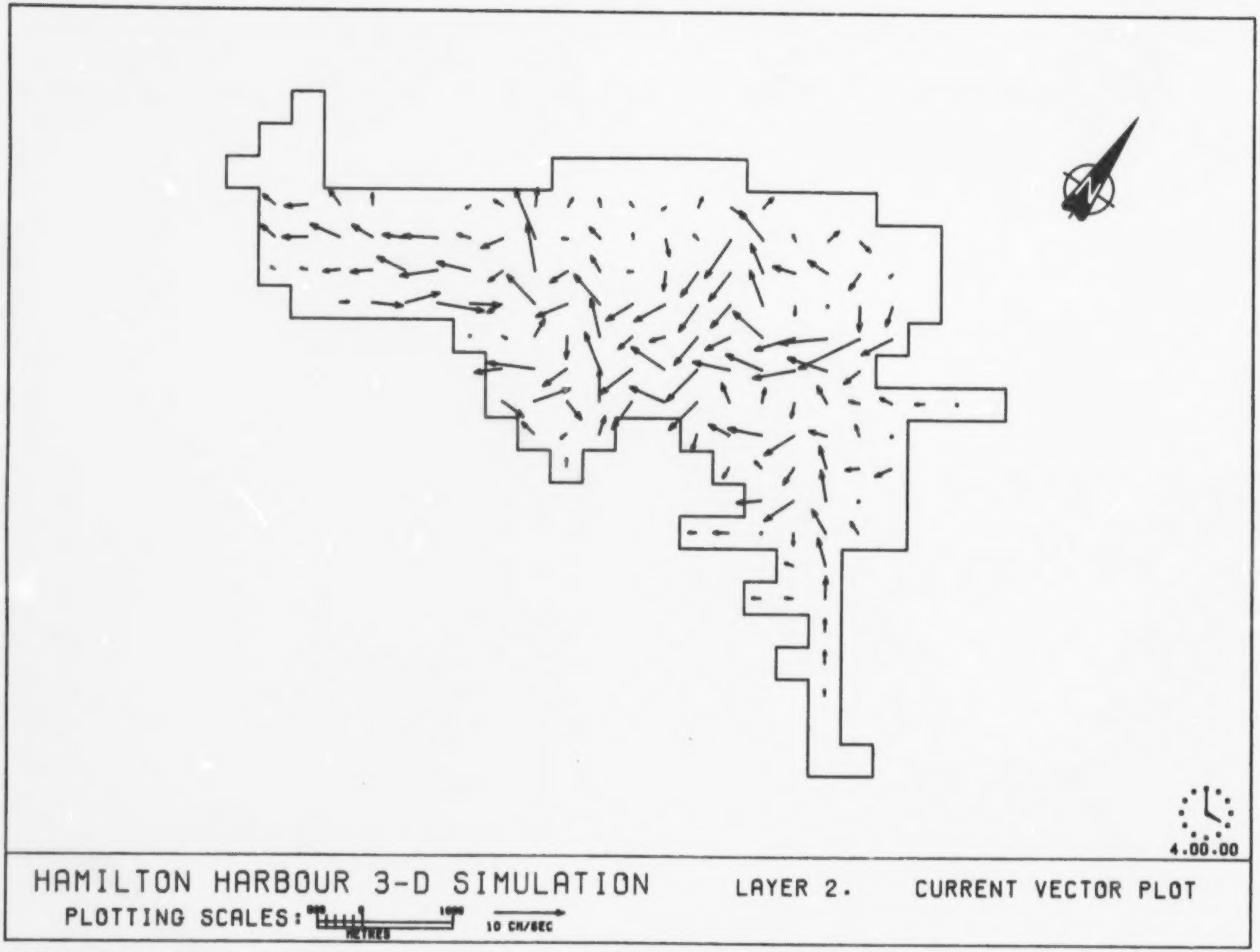

4.00.00
HAMILTON HARBOUR 3-D SIMULATION
LAYER 1.
CURRENT VECTOR PLOT
PLOTTING SCALES:
500
0
1000
METRES
10 CM/SEC

FIGURE 12a - MODEL CURRENTS IN LAYER 1, 4 hr AFTER SPINUP, RUN Nº 4B



4.00.00
HAMILTON HARBOUR 3-D SIMULATION
LAYER 2.
CURRENT VECTOR PLOT
PLOTTING SCALES:
0
1000
METRES
10 CM/SEC

FIGURE 12b - MODEL CURRENTS IN LAYER 2, 4 hr AFTER SPINUP, RUN Nº 4B

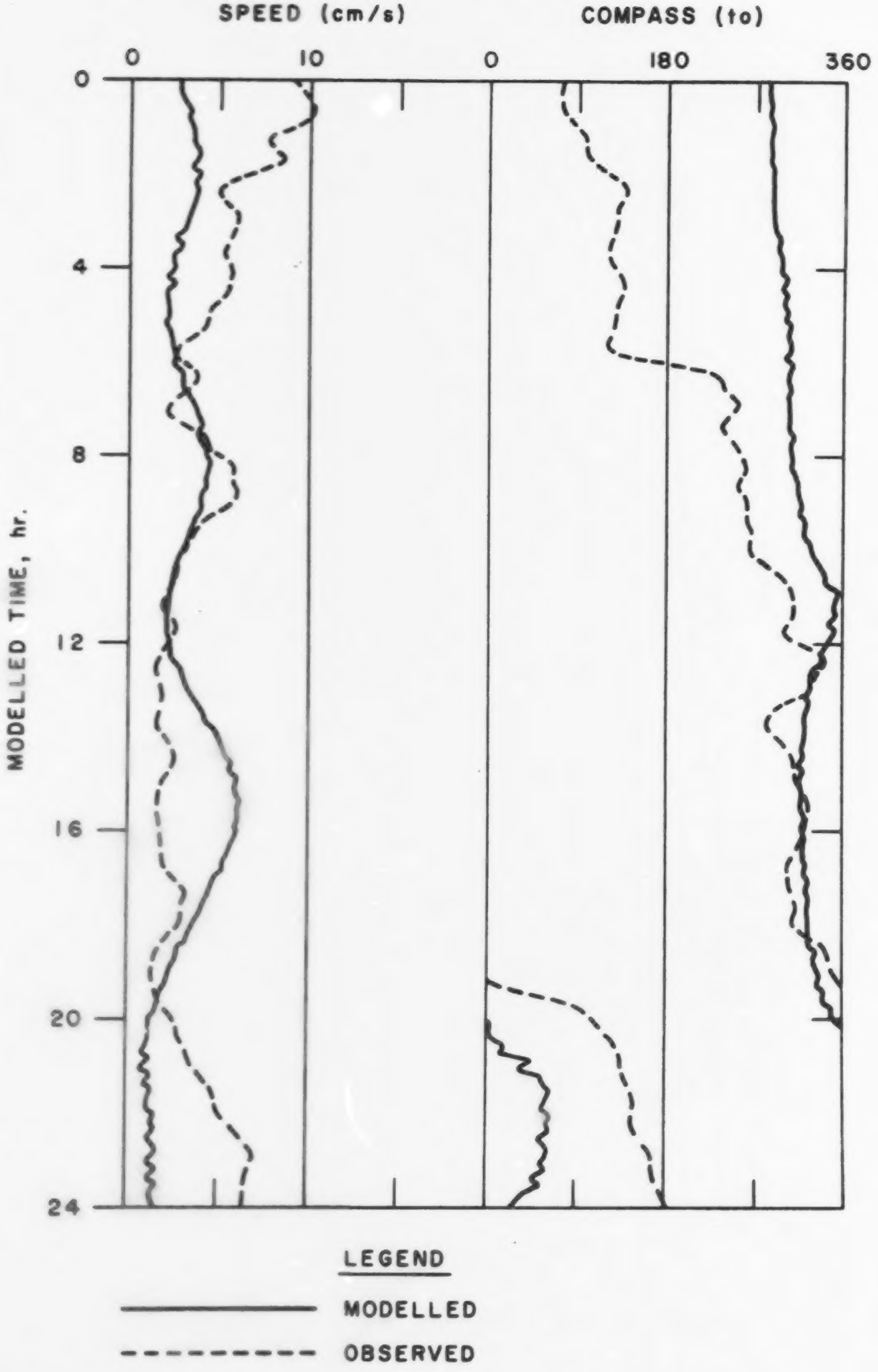


FIGURE 13a - COMPARISON OF OBSERVED AND MODELLED VELOCITIES AT LOCATION (16, 11, 2), JUNE 1976, FIRST 24 hr.

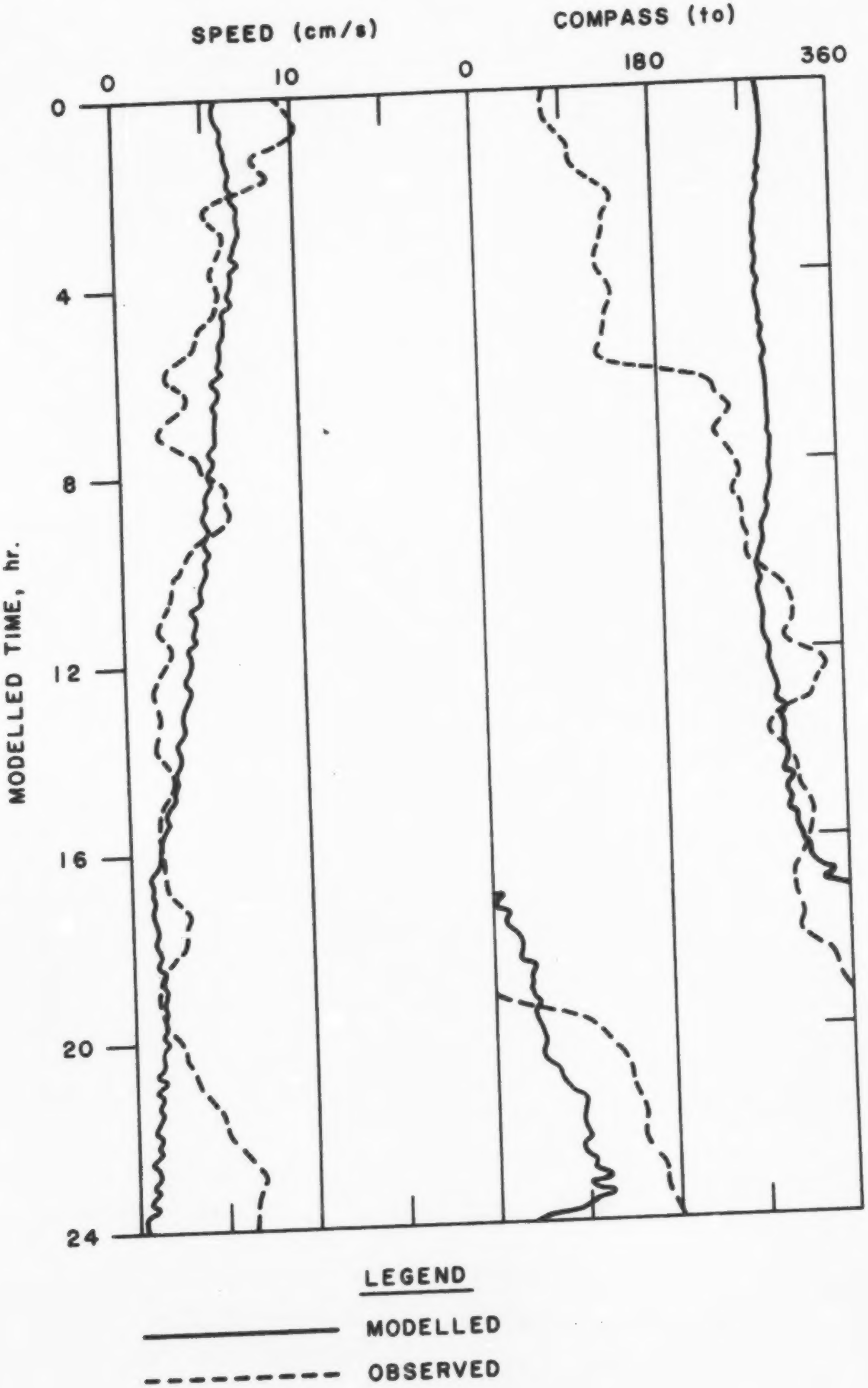


FIGURE 13b – COMPARISON OF OBSERVED AND MODELLED VELOCITIES AT LOCATION U (18, 11, 2) V (18, 12, 2), JUNE 1976, FIRST 24 hr.

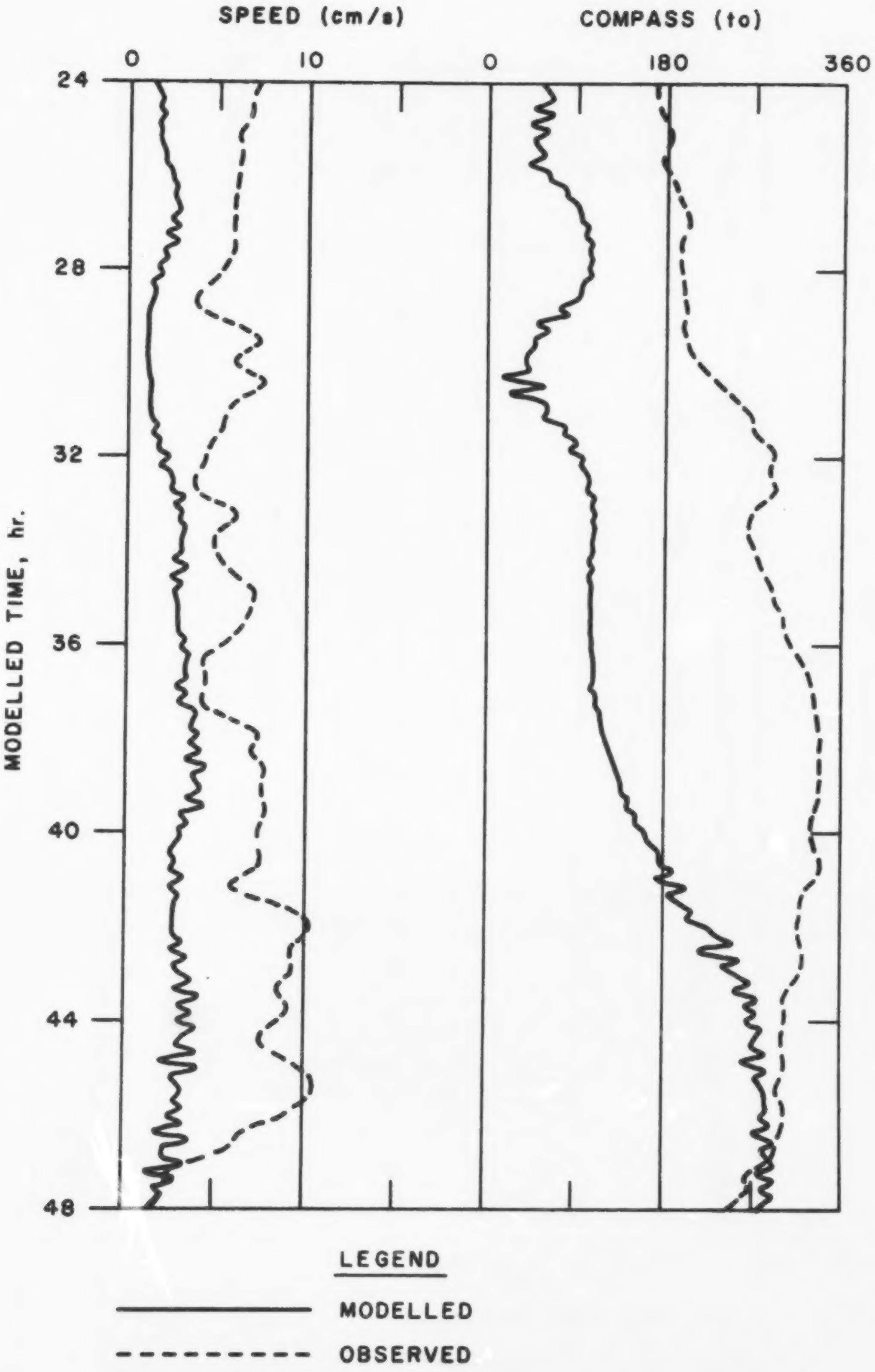


FIGURE 13c - COMPARISON OF OBSERVED AND MODELLED VELOCITIES AT LOCATION (16, 11, 2), JUNE 1976, SECOND 24 hr.

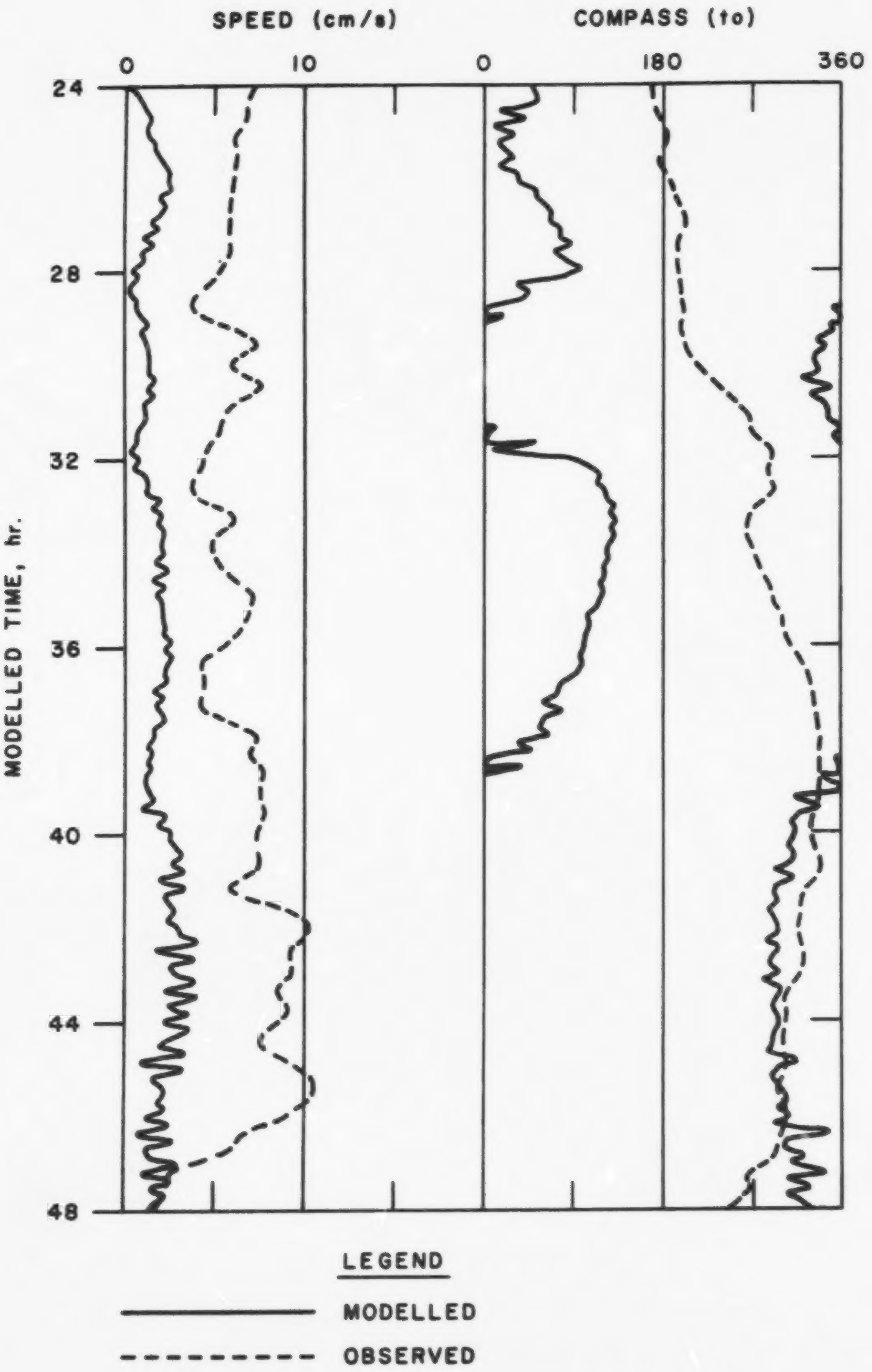
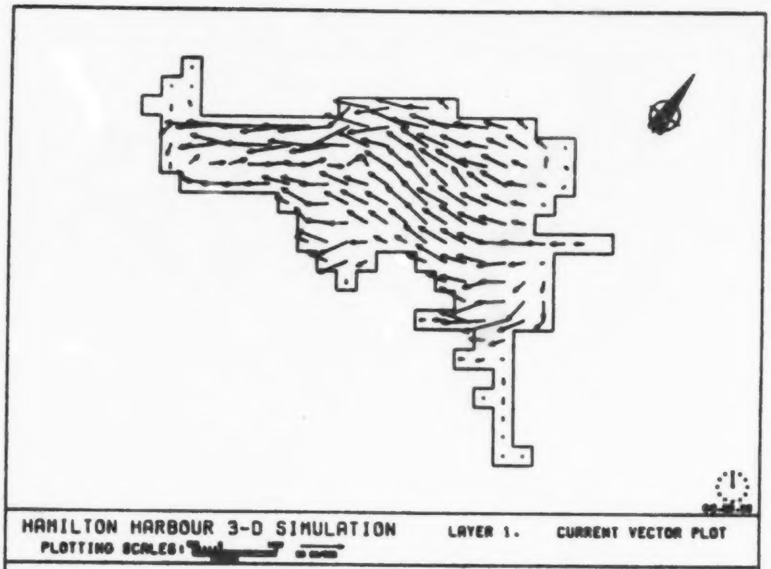
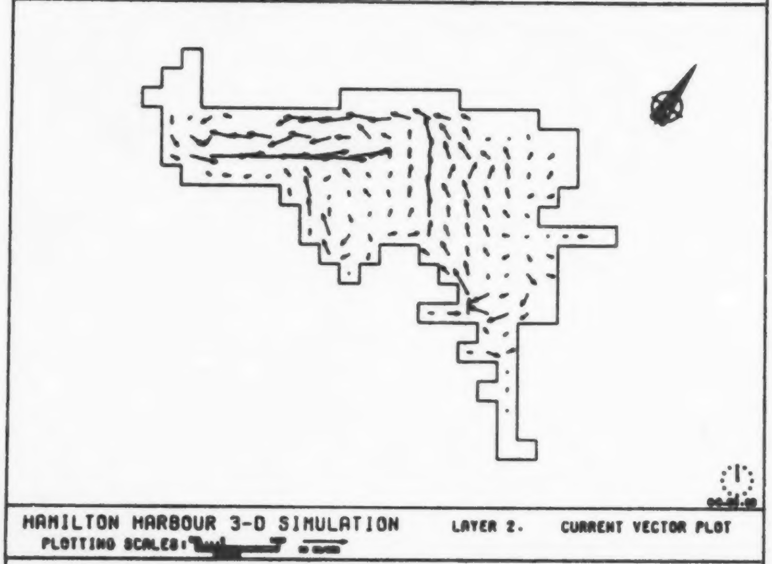


FIGURE 13d - COMPARISON OF OBSERVED AND MODELLED VELOCITIES AT LOCATION U (18, 11, 2) V (18, 12, 2), JUNE 1976, SECOND 24 hr.


HAMILTON HARBOUR 3-D SIMULATION
LAYER 1.
CURRENT VECTOR PLOT
PLOTTING SCALES:


HAMILTON HARBOUR 3-D SIMULATION
LAYER 2.
CURRENT VECTOR PLOT
PLOTTING SCALES:

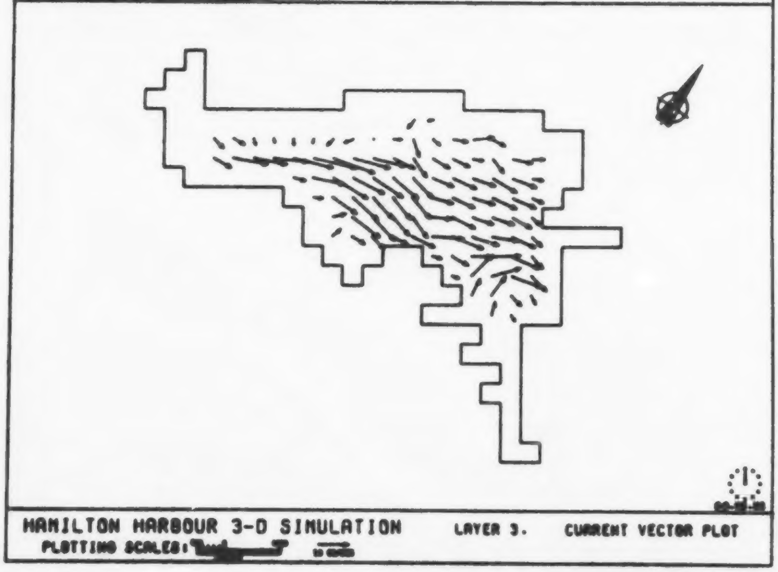

HAMILTON HARBOUR 3-D SIMULATION
LAYER 3.
CURRENT VECTOR PLOT
PLOTTING SCALES:

FIGURE 14a - VECTOR PLOTS OF MODELLED CURRENTS AFTER 24 HOURS OF SPIN-UP TIME (AT THE BEGINNING OF THE APPLICATION OF REAL-TIME DATA, 1200 hr. ON JUNE 12, 1976)

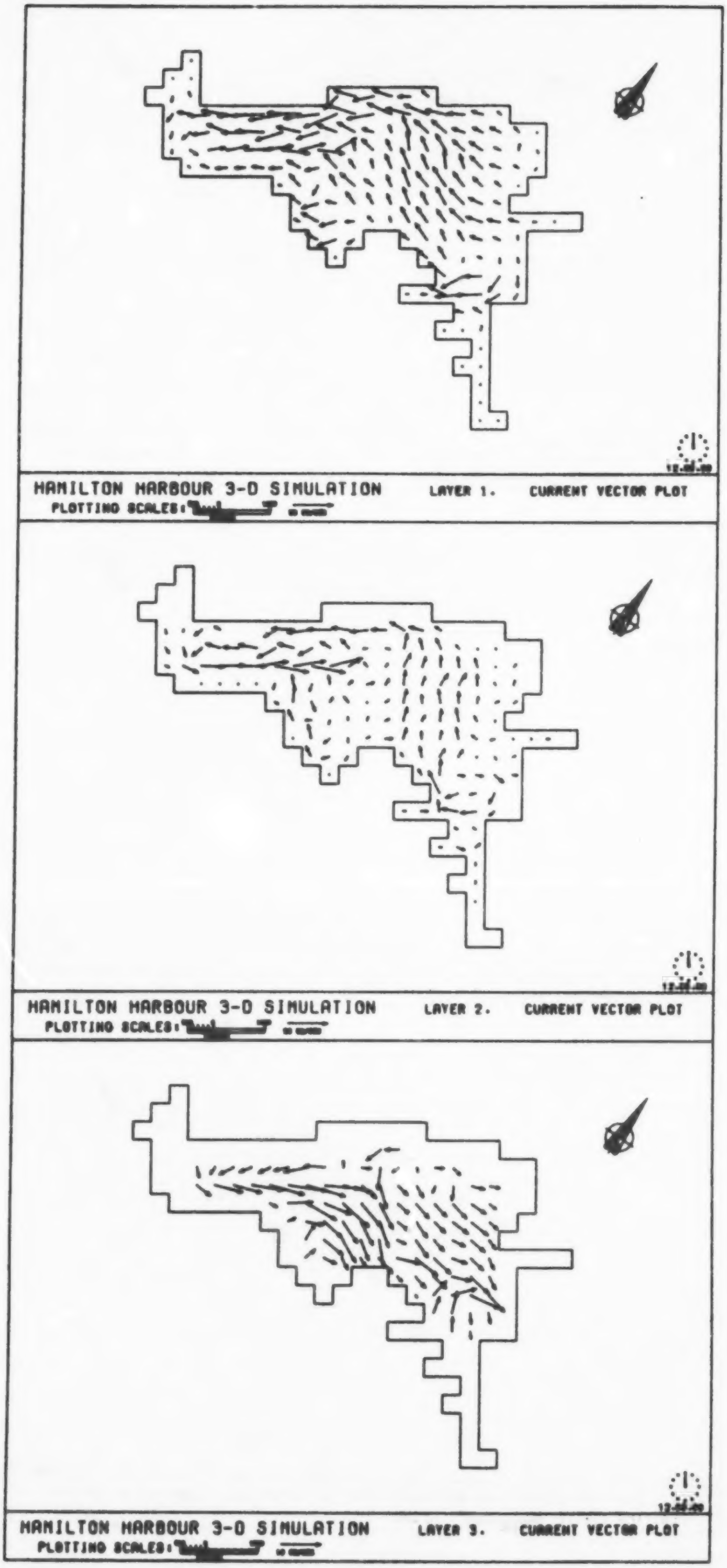
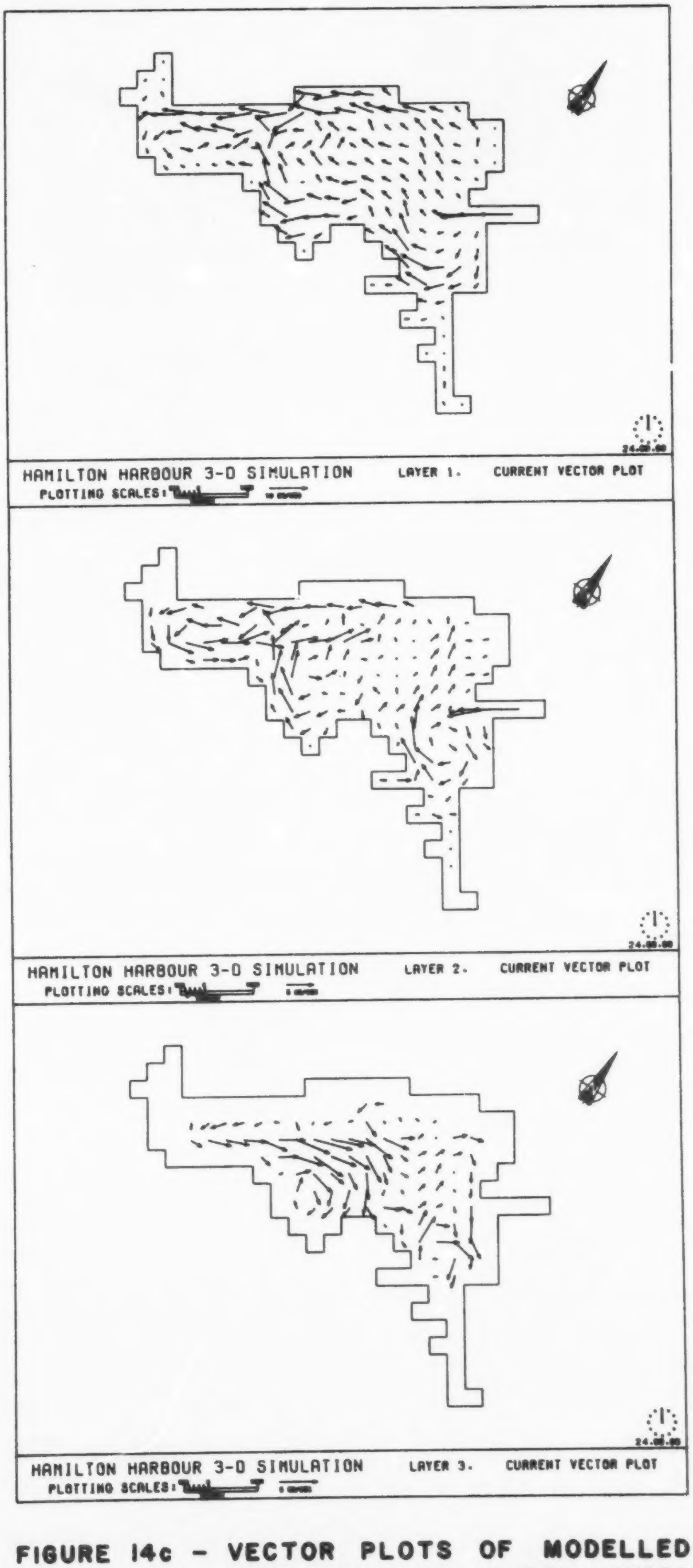


FIGURE 14b - VECTOR PLOTS OF MODELLED CURRENTS IN THE THREE LAYERS AFTER 12 hr. MODELLED TIME



HAMILTON HARBOUR 3-D SIMULATION LAYER 1. CURRENT VECTOR PLOT

PLOTTING SCALES:

HAMILTON HARBOUR 3-D SIMULATION LAYER 2. CURRENT VECTOR PLOT

PLOTTING SCALES:

HAMILTON HARBOUR 3-D SIMULATION LAYER 3. CURRENT VECTOR PLOT

PLOTTING SCALES:

FIGURE 14c – VECTOR PLOTS OF MODELLED CURRENTS IN THE THREE LAYERS AFTER 24 hr. MODELLED TIME

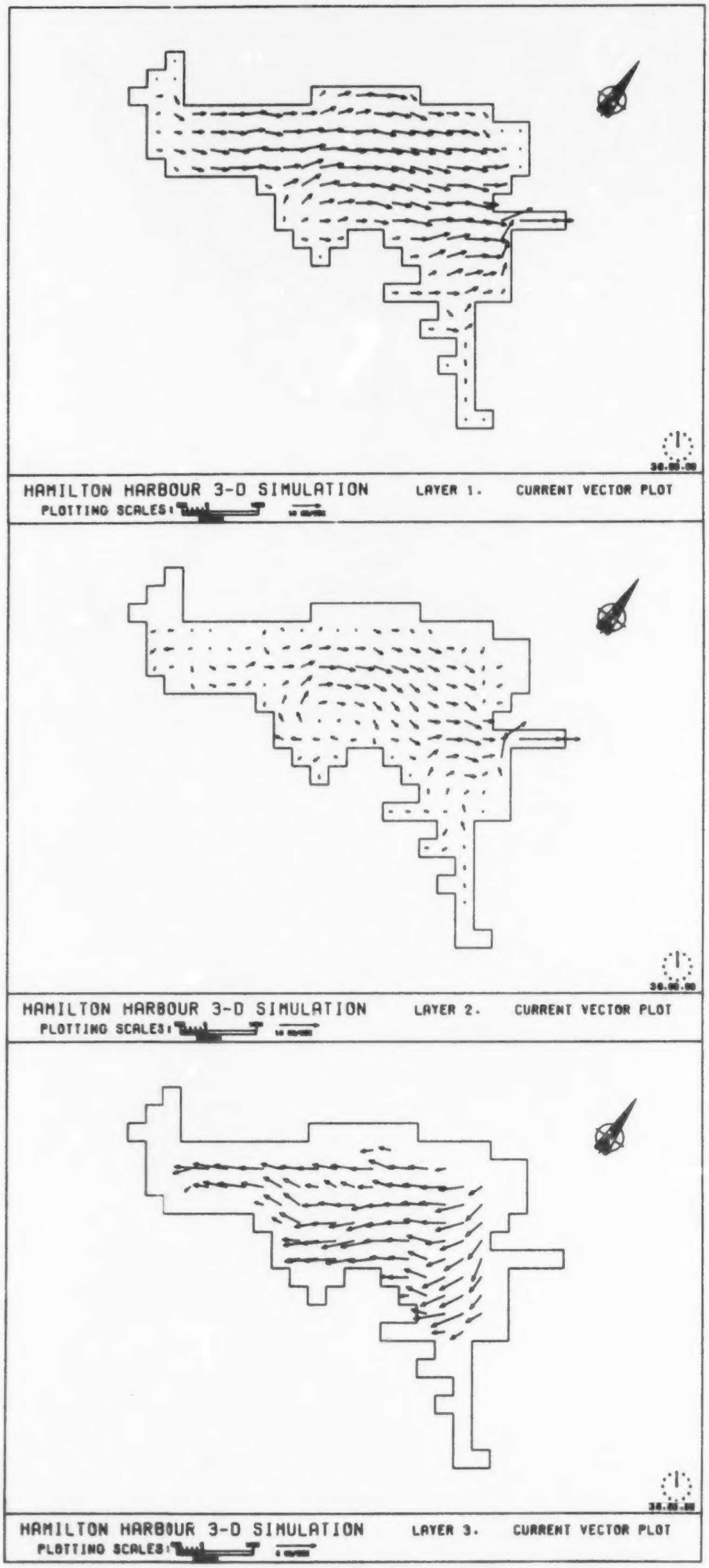
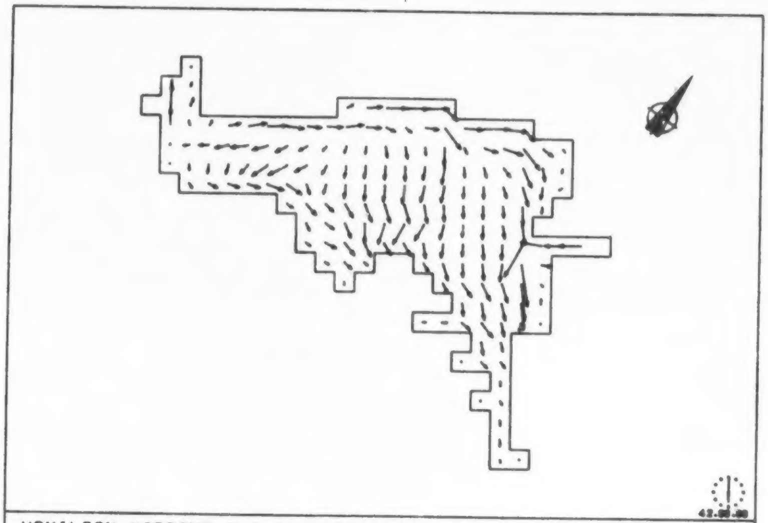
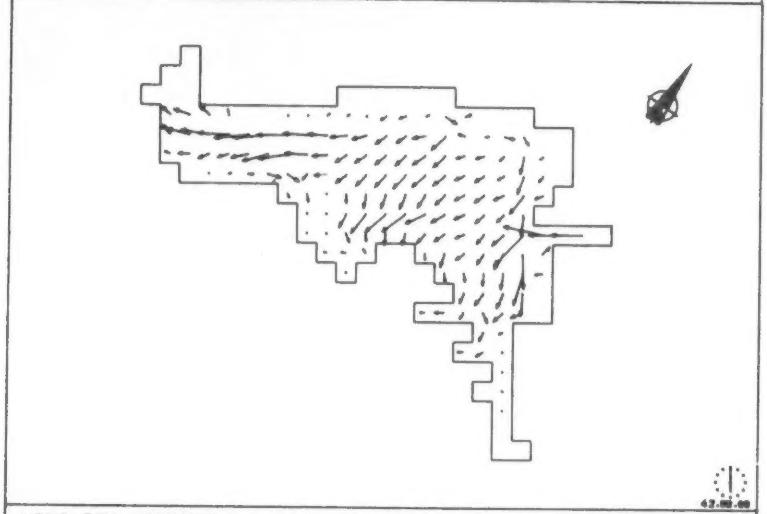

36:00:00
HAMILTON HARBOUR 3-D SIMULATION
LAYER 1.
CURRENT VECTOR PLOT
PLOTTING SCALES:
36:00:00
HAMILTON HARBOUR 3-D SIMULATION
LAYER 2.
CURRENT VECTOR PLOT
PLOTTING SCALES:
36:00:00
HAMILTON HARBOUR 3-D SIMULATION
LAYER 3.
CURRENT VECTOR PLOT
PLOTTING SCALES:

FIGURE 14d - VECTOR PLOTS OF MODELLED CURRENTS IN THE THREE LAYERS AFTER 36 hr. MODELLED TIME



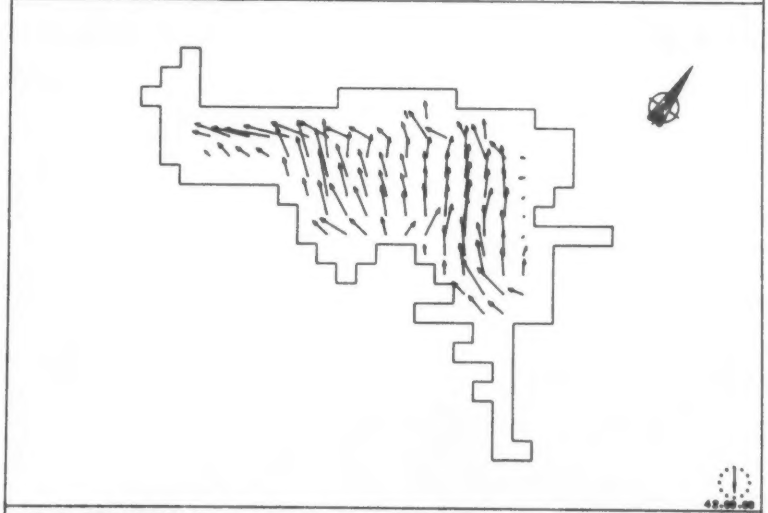
HAMILTON HARBOUR 3-D SIMULATION LAYER 1. CURRENT VECTOR PLOT

PLOTTING SCALES:



HAMILTON HARBOUR 3-D SIMULATION LAYER 2. CURRENT VECTOR PLOT

PLOTTING SCALES:



HAMILTON HARBOUR 3-D SIMULATION LAYER 3. CURRENT VECTOR PLOT

PLOTTING SCALES:

FIGURE 14e - VECTOR PLOTS OF MODELLED CURRENTS IN THE THREE LAYERS AFTER 42 hr. MODELLED TIME

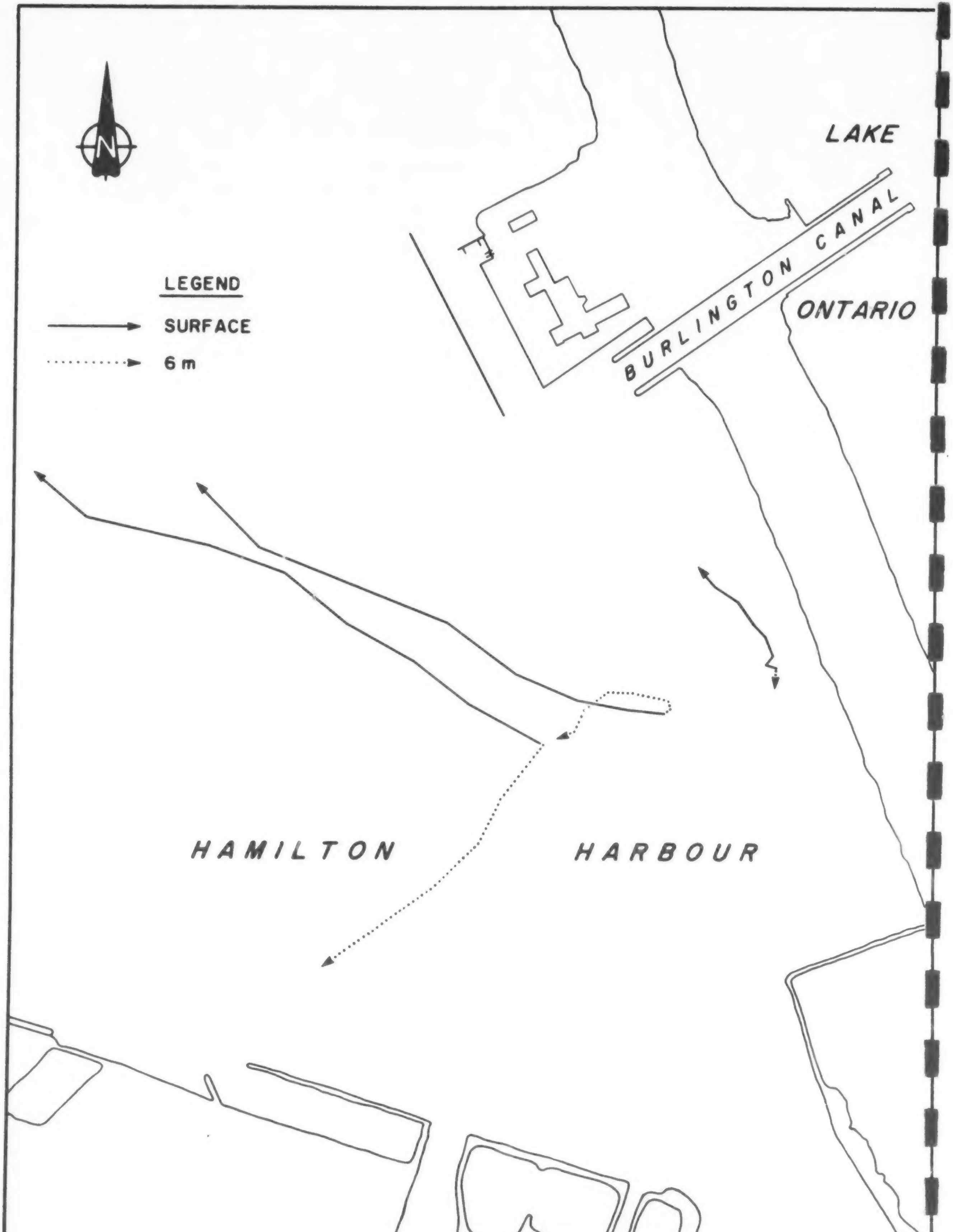

LAKE
ONTARIO
BURLINGTON CANAL
LEGEND
SURFACE
6 m
HAMILTON
HARBOUR
N

FIGURE 15a - RESULTS OF DROGUE TRACKINGS IN HAMILTON HARBOUR ON SEPTEMBER 4, 1979, EAST WIND CONDITIONS

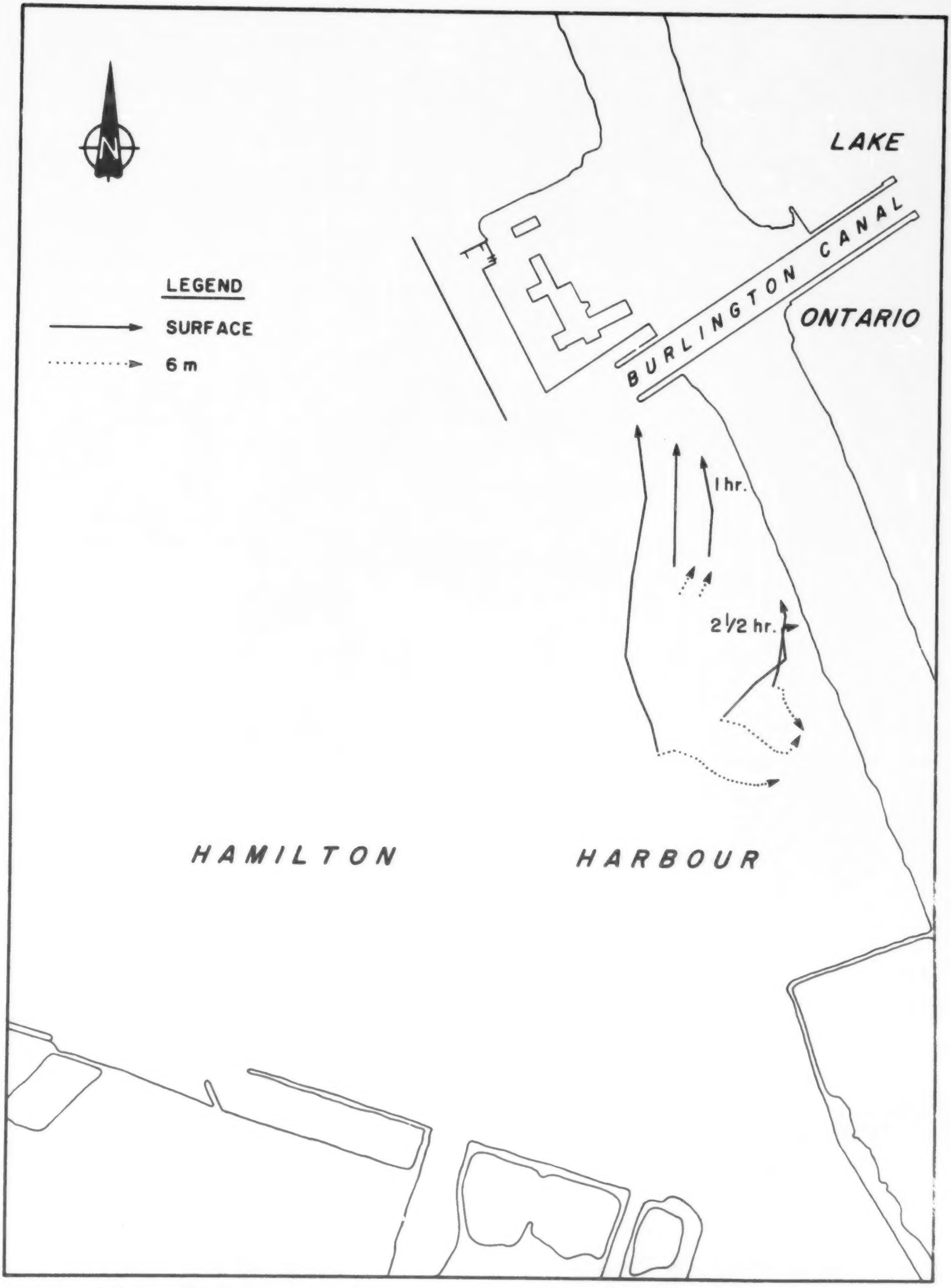

LAKE
ONTARIO
BURLINGTON CANAL
LEGEND
SURFACE
6 m
1 hr.
2 1/2 hr.
HAMILTON HARBOUR
N

FIGURE 15b - RESULTS OF DROGUE TRACKINGS IN HAMILTON HARBOUR ON SEPTEMBER 27, 1979, SOUTHWEST WIND CONDITIONS

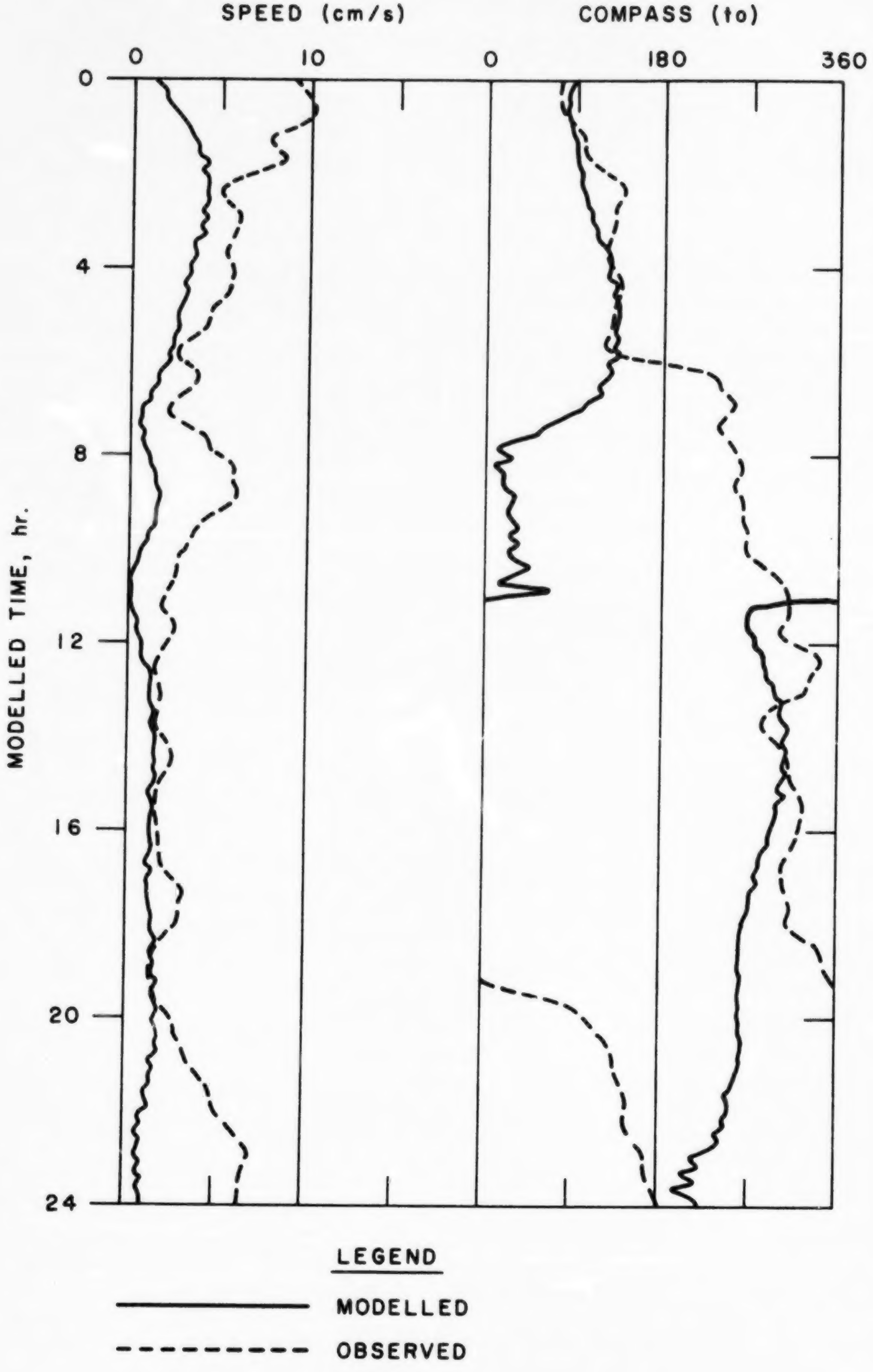


FIGURE 16a - COMPARISON OF OBSERVED AND MODELLED VELOCITIES AT LOCATION U (18, 12, 3) V (17, 12, 3), JUNE 1976, FIRST 24 hr.

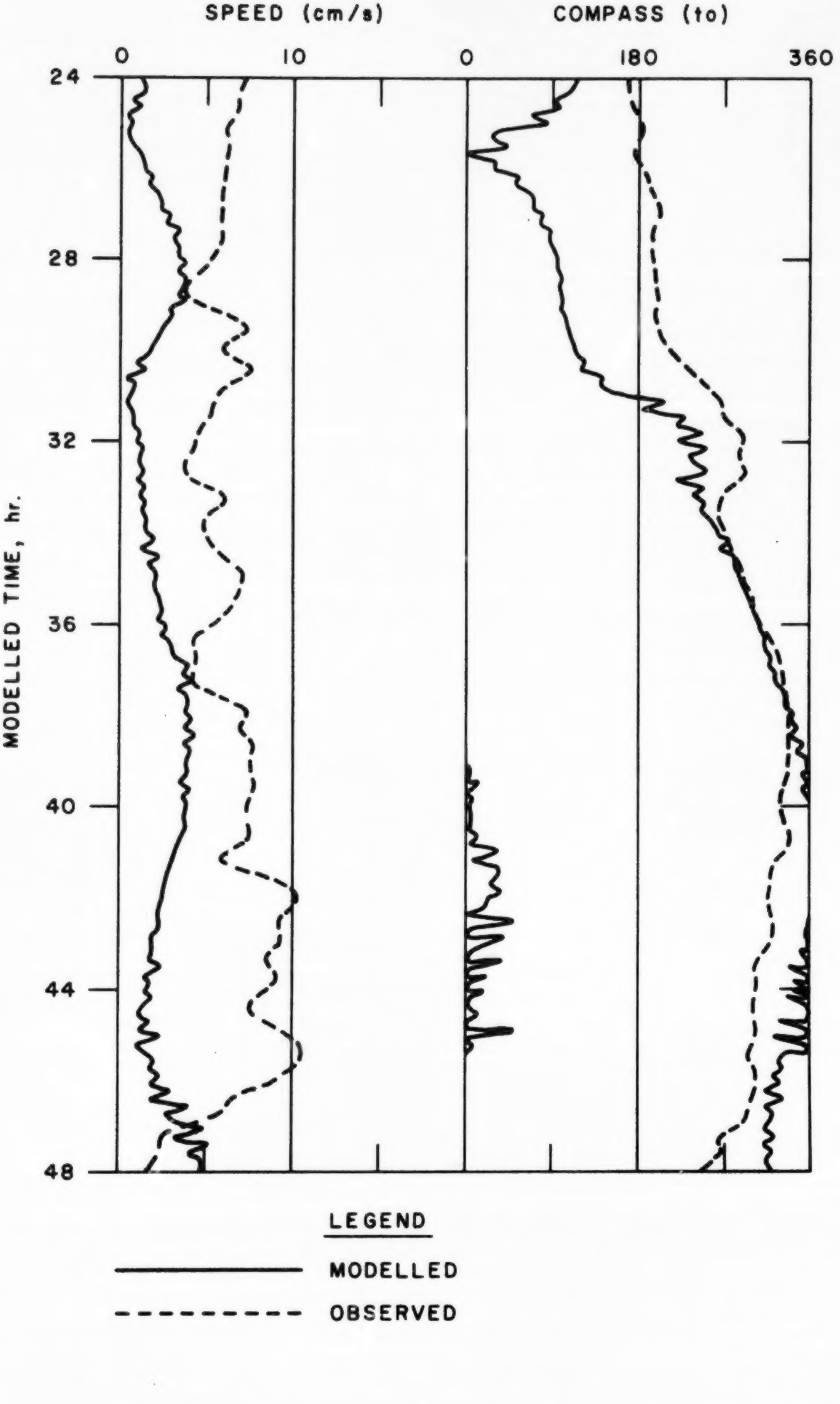


FIGURE 16b - COMPARISON OF OBSERVED AND MODELLED VELOCITIES AT LOCATION (17, 12, 2), JUNE 1976, SECOND 24 hr.

HAMILTON HARBOUR STUDY

1977

VOLUME I

SECTION H

WATER MOVEMENTS

SUMMARY

Physical processes of Hamilton Harbour were studied during 1976 and 1977 by operating self-recording current instruments at a mid-harbour location and in the Burlington and Desjardins Canals. In the harbour, the resultant currents varied from 0.7 to 1.8 $cm.s^{-1}$; in Burlington Canal, they ranged between 0.6 and 13.4 $cm.s^{-1}$ and in Desjardins Canal, they were from 3.3 to 8.1 $cm.s^{-1}$. Both the connecting canals exhibited faster currents compared to the mid-harbour and lake coastal regions, probably due to the constriction of the canals.

Flows through the two canals were estimated in both directions from measured currents. The exchange through Burlington Canal was an order of magnitude larger than through Desjardins Canal. Net flow through Burlington Canal was 0.2 to 1.4% of the harbour volume per day, towards Lake Ontario. Net flow through Desjardins Canal varied from 0.07 to 0.15% of the harbour volume per day, towards the harbour.

The spectral analysis of the currents at the mid-harbour showed diurnal and semi-diurnal periods and the effects of Lake Ontario. The analysis for the two canal locations indicated predominant tidal effects as well as the first two oscillation modes of Lake Ontario. At Burlington Canal, significant coherences were observed on occasions for periods from 2 to 30 h between different depths from June to August 1976, including vertical homogeneity of currents and water temperature inspite of the weak thermal stratification in the canal. Such a vertical homogeneity in other years may or may not exist.

The mean water temperatures in the harbour ranged from 17.6 to 19.2°C during summer 1976. Burlington Canal mean water temperatures ranged from 6.6 to 20.9°C, June to November 1976-77. A weak stratification of the Canal was observed during summer 1976, followed by no stratification from October to November 1976. The mean water temperatures in Desjardin Canal varied from 4.5 to 20.8°C from May to November 1976.

INTRODUCTION

Hamilton Harbour is a natural harbour located at the western corner of Lake Ontario. It contains 280 x 10^6 m^3 of fresh water and has a mean depth of 13 m. The harbour is connected to Lake Ontario by the Burlington Canal and to Cootes Paradise by the Desjardins Canal (see Figure 1). The port is very important to heavy industry on the south shore. The industry uses and recirculates 27 $m^3 . s^{-1}$ (0.8% of harbour volume per day) of harbour water. Several creeks discharge 4.1 $m^3 . s^{-1}$ of water to the harbour while the municipal sewage outfalls add 3.2 $m^3 . s^{-1}$ of treated effluents.

The Ontario Ministry of the Environment (MOE) has been studying the biological, chemical and physical processes of the harbour and how their complex interactions affect water quality (MOE, 1974, 1975 and 1977). During summer of each year, hypolimnion waters experience oxygen depletion. Polak and Haffner (1978) concluded that the exchange of water between the harbour and the lake provides the much needed dissolved oxygen to the harbour. Lake-harbour exchange was estimated to be 1% of the harbour volume per day while the net flow towards the lake was 0.5% of the harbour volume per day during September 1975 (Kohli, 1979).

This report discusses the results of the 1976-77 current meter operations in the harbour, Burlington and Desjardins Canals, including lake-harbour and harbour-Cootes Paradise exchange and the physical processes responsible for the currents and is a continuation of the series of reports on Hamilton Harbour physical data (MOE, 1974, 1975 and 1977; Kohli, 1978 and 1979).

Table 1 presents the current meter operations in Hamilton Harbour, Burlington and Desjardins Canals during 1976-77. All current meter sites are shown in Figures 1 to 4 and 7. Locations 1117, 1116, 1101 and 1102 were on the same tower in Burlington Canal at different depths (see Table 1). All instruments were operated in the epilimnion, except 1102 which was in the hypolimnion. All data collected were numerically smoothed (Kohli, 1978) and then partitioned into monthly data sets (records). Statistical analyses of water movements and temperatures were performed to determine the spatial and temporal characteristics. Currents at the Burlington Canal locations were examined to compute the lake harbour exchange using the excursion episode method (Kohli, 1979). Estimates of the flow through Desjardins Canal were made using average currents and the approximate cross-sectional area of the canal.

RESULTS[1]

CURRENTS

HAMILTON HARBOUR

Figure 1 shows the resultant southerly direction of currents during the stratified summer months of June to August 1976-77. Similar observations were made during August and September 1975 (Kohli, 1978). The resultant currents at the mid-harbour location (1104) varied from 0.7 to 1.8 $cm.s^{-1}$ while the arithmetic average speed ranged from 1.7 to 4.8 $cm.s^{-1}$ (see Table 2). The maximum speed recorded at this location during 1976-77 summers was 28 $cm.s^{-1}$. The persistence factor varied from 0.11 to 0.40 during this study. The results of the present investigation compared favourably with the previous study (Kohli, 1978).

BURLINGTON CANAL

Table 3 and Figures 2-4 present the summary of currents in Burlington Canal during 1976 and 1977. Figures 2 and 3 indicate that the resultant currents at the top two locations, 1117 and 1116 (8.5 m and 7.5 m from bottom) were towards the lake for the entire period of study. However at 1101, 6.1 m from the bottom, the resultant currents were toward the lake from June to November 1976, but they were toward the harbour from May to July 1977 (see Figure 4). The direction of net currents at 2.1 m from the bottom (the lowest location 1102), was towards the canal wall during June and July 1976. At this site (1102), the recorded currents were integrated over 10 minutes and were less than 2 cm.s^{-1} for approximately 96% of the time during June and July 1976. Therefore, most of the recorded speeds were actually less than the threshold speed of the Plessey Current Meters (3 cm.s^{-1}). When the current speed is less than the instrument threshold speed, the direction vane can assume any random position and the direction recording becomes meaningless. Therefore, the computed resultant current direction towards the canal wall, in this case, was meaningless. Thus it may be concluded that the net currents in the canal are predominantly towards the lake.

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[1] Detailed current frequency tables for the various current meter locations have been published in Kohli, 1980

At location 1117 (8.5 m from bottom) the resultant currents ranged from 0.9 to 13.4 cm.s^{-1} while the arithmetic average speed varied from 7.6 to 16.7 cm.s^{-1} (see Table 3). The maximum speed recorded during the study ranged from 25 to 83 cm.s^{-1}. At location 1116 (7.5 m from bottom), the resultant currents varied from 2.3 to 6.8 cm.s^{-1} while the arithmetic average speed ranged from 7.8 to 14.7 cm.s^{-1} (see Table 3). The maximum speed recorded during the study varied from 48 to 129 cm.s^{-1}. The resultant current at 6.1 m from the bottom (location 1101) varied from 0.6 to 7.6 cm.s^{-1}, while the arithmetic average speed ranged from 6.9 to 14.1 cm.s^{-1} (see Table 3). The maximum speed recorded at this level was between 44 and 126 cm.s^{-1}. The resultant speed at 2.1 m from the bottom (location 1102) was 0.5 cm.s^{-1} during June and July 1976. The arithmetic average speed during June 1976 was 0.6 cm.s^{-1} and during July 1976, it was 0.7 cm.s^{-1}. The level being closer to the bottom registered the slowest currents in the canal. More specifically, the currents here were negligible for 49% of the time and less than 2 cm.s^{-1} for 95% of the time during June 1976. In July 1976, the currents were negligible for 30% of the time and less than 1 cm.s^{-1} for 70% of the time. The maximum speed recorded was 25 cm.s^{-1} during June 1976 and 3 cm.s^{-1} during July 1976. In view of the very small currents (less than the instrument threshold speed of 3.0 cm. s^{-1}) persisting over longer periods of time, the results of the lowest location (1102) may be used but with due caution.

The results of the top three current meters (1117, 1116 and 1101) are comparable to the earlier study (Kohli, 1978). The resultant currents of 0.6 to 13.4 cm.s^{-1} (present study) compare well with 1.1 to 15.2 cm.s^{-1} during 1972 to 1975 (Kohli, 1978). The maximum speed recorded during the present study was 129 cm.s^{-1} which compares well with the 144 cm.s^{-1} of the previous study. These faster currents in the canal may be attributed to the canal constriction (van de Kreeke, 1976) and the Helmholtz mode of the harbour (Freeman, Hamblin and Murthy, 1974).

Careful examination of the current statistics of Burlington Canal (see Table 3) shows that the magnitude of the resultant current, as well as the arithmetic average speed, decreases with depth. Figures 2, 3 and 4 show that the resultant currents in Burlington Canal were generally towards the lake at all three levels, except during May to July 1977 at location 1101 (see Figure 4), when the resultant currents were going towards the harbour. This shift in direction of the resultant currents at 1101 and the presence of a layered flow system in Burlington Canal during summer 1977, in contrast to the unidirectional flow during the summer 1976, was confirmed by the mean water temperatures (see Figure 5). A sharp temperature drop of 8-9^{o}C was observed between locations 1116 and 1101 during summer 1977 while the temperature drop between the same locations and during the same period of 1976 was 1-2^{o}C.

Flows through Burlington Canal were computed by the excursion-episode method (Kohli, 1979) and the results for the period June to November 1976, are presented in Table 4. As expected, the net exchange was towards the lake. The total exchange varied from 1.1 to 1.6% of the harbour volume per day, while the net exchange towards the lake ranged from 0.2 to 1.4% of the harbour volume per day (see Figure 6). These results compare well with the previous estimates when the total exchange was 1.0% of the harbour volume per day, while the net exchange towards the lake was 0.5% of the harbour volume per day (Kohli, 1979) during September 1975. Harris et al (1979) computed the average mass exchange through Burlington Canal, based on the mass balance of total dissolved solids in the harbour over a year. Their results are compared with the present study and Kohli (1979) in Table 5. Harris' calculations assume the harbour to be in steady state over a year - an unreasonable assumption in an otherwise dynamic harbour. Table 5 shows that Harris' flow estimates towards the lake and the harbour are 2 and 7 times larger than the excursion-episode estimates, but their net flow estimates toward the lake are 40% of those by the excursion-episode method. As the excursion-episode method computes the flows from direct measurements in the canal, taking account of the periodic transport, it is considered a better method.

DESJARDINS CANAL

Desjardins Canal is located at the western end of Hamilton Harbour (see Figures 1 and 7), connecting the harbour to Cootes Paradise. A single current meter at mid-depth (location 1109) operated under the railway bridge, from 27 May to 24 November 1979. Only one instrument could be installed due to the shallow depth of 3.7 m. A summary of current statistics is presented in Table 6. The resultant currents varied from 3.3. to 8.1 cm.s^{-1}, while the arithmetic average speed ranged from 9.8 to 24.2 cm.s^{-1}. The maximum speed recorded was 88 cm.s^{-1}. The faster currents in the canal may be attributed to the constriction (van de Kreeke, 1976).

Based on the average current speed towards the Harbour and Cootes Paradise, with the corresponding percentages of occurence, the flow in both directions was computed for the period May to November, 1976. As such estimates in Burlington Canal were 2 to 3 times larger than the excursion-episode method (Kohli, 1978), a correction factor of 2.5 has been applied to obtain the more realistic estimates of the flow presented in Table 7. Although the correction factor was transposed from Burlington Canal to Desjardins Canal, it produced results that were compatible with the water balance of Cootes

Paradise (see discussions below). The total exchange through the canal varied from 0.07 to 0.15% of the harbour volume per day (see Figure 8), while the net exchange was 0.02 to 0.05% of the harbour volume per day (average net flow of 1.11 $m^3.s^{-1}$), towards the harbour. The exchange through the Burlington Canal is an order of magnitude larger than through the Desjardins Canal.

Spencer Creek discharges an average of 0.81 $m^3.s^{-1}$ from June to November (1961-75), while the Dundas STP discharges an average of 0.12 $m^3.s^{-1}$ into Cootes Paradise (Semkin et al, 1976). Thus, Spencer Creek and Dundas STP, together add 0.93 $m^3.s^{-1}$ to Cootes Paradise while the net average outflow from Cootes Paradise to Hamilton Harbour was computed as 1.11 $m^3.s^{-1}$. The small difference of 0.18 $m^3s.^{-1}$ may be attributed to other smaller creeks flowing into Cootes Paradise, ground water, precipitation or to the choice of the specific correction factor used for computing flows in Desjardins Canal.

AUTOSPECTRA

HAMILTON HARBOUR

Table 8 presents a summary of the major spectral periods observed at the mid-harbour location (1104). Diurnal (24.0 h) and semi-diurnal (12.0 h) periodic motions were observed in the east-west directions during July 1976. Semi-diurnal oscillations were also observed along the north-south direction during June 1976 and July 1977. These are associated with the lunar tidal motions. The 17.1 h (August 1976) and 20.0 h (June 1977) periods along the north-south direction were due to the lake-wide seiche. In June 1977, along the east-west direction, 3.6 and 4.6 h periods were significant and these may be due to the lower modes of free oscillations of Lake Ontario (Rockwell, 1966). The effects of Lake Ontario are therefore observed in the harbour.

BURLINGTON CANAL

A summary of significant spectral periods in Burlington Canal is presented in Table 9. The 12.0, 5.2 and 3.2 h were the most predominant periodicities observed at locations 1117, 1116 and 1101 day, while the net exchange towards the lake was 0.5% of the harbour volume per day (Kohli, 1979) during September 1975. Harris et al (1979) computed the average mass exchange through Burlington Canal, based on the mass balance of total dissolved solids in the harbour over a year. Their results are compared with the present study and Kohli (1979) in Table 5. Harris' calculations assume the harbour to be in steady state over a year - an unreasonable assumption in an otherwise dynamic harbour. Table 5 shows that Harris' flow estimates towards the lake and the harbour are 2 and 7 times larger than the excursion-episode estimates, but their net flow estimates toward the lake are 40% of those by the excursion-episode method. As the excursion-episode method computes the flows from direct measurements in the canal, taking account of the periodic transport, it is considered a better method.

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Desjardins Canal is located at the western end of Hamilton Harbour (see Figures 1 and 7), connecting the harbour to Cootes Paradise. A single current meter at mid-depth (location 1109) operated under the railway bridge, from 27 May to 24 November 1979. Only one instrument could be installed due to the shallow depth of 3.7 m. A summary of current statistics is presented in Table 6. The resultant currents varied from 3.3. to 8.1 cm.s^{-1}, while the arithmetic average speed ranged from 9.8 to 24.2 cm.s^{-1}. The maximum speed recorded was 88 cm.s^{-1}. The faster currents in the canal may be attributed to the constriction (van de Kreeke, 1976).

Based on the average current speed towards the Harbour and Cootes Paradise, with the corresponding percentages of occurence, the flow in both directions was computed for the period May to November, 1976. As such estimates in Burlington Canal were 2 to 3 times larger than the excursion-episode method (Kohli, 1978), a correction factor of 2.5 has been applied to obtain the more realistic estimates of the flow presented in Table 7. Although the correction factor was transposed from Burlington Canal to Desjardins Canal, it produced results that were compatible with the water balance of Cootes

Paradise (see discussions below). The total exchange through the canal varied from 0.07 to 0.15% of the harbour volume per day (see Figure 8), while the net exchange was 0.02 to 0.05% of the harbour volume per day (average net flow of 1.11 $m^3.s^{-1}$), towards the harbour. The exchange through the Burlington Canal is an order of magnitude larger than through the Desjardins Canal.

Spencer Creek discharges an average of 0.81 $m^3.s^{-1}$ from June to November (1961-75), while the Dundas STP discharges an average of 0.12 $m^3.s^{-1}$ into Cootes Paradise (Semkin et al, 1976). Thus, Spencer Creek and Dundas STP, together add 0.93 $m^3.s^{-1}$ to Cootes Paradise while the net average outflow from Cootes Paradise to Hamilton Harbour was computed as 1.11 $m^3.s^{-1}$. The small difference of 0.18 $m^3s.^{-1}$ may be attributed to other smaller creeks flowing into Cootes Paradise, ground water, precipitation or to the choice of the specific correction factor used for computing flows in Desjardins Canal.

AUTOSPECTRA

HAMILTON HARBOUR

Table 8 presents a summary of the major spectral periods observed at the mid-harbour location (1104). Diurnal (24.0 h) and semi-diurnal (12.0 h) periodic motions were observed in the east-west directions during July 1976. Semi-diurnal oscillations were also observed along the north-south direction during June 1976 and July 1977. These are associated with the lunar tidal motions. The 17.1 h (August 1976) and 20.0 h (June 1977) periods along the north-south direction were due to the lake-wide seiche. In June 1977, along the east-west direction, 3.6 and 4.6 h periods were significant and these may be due to the lower modes of free oscillations of Lake Ontario (Rockwell, 1966). The effects of Lake Ontario are therefore observed in the harbour.

BURLINGTON CANAL

A summary of significant spectral periods in Burlington Canal is presented in Table 9. The 12.0, 5.2 and 3.2 h were the most predominant periodicities observed at locations 1117, 1116 and 1101 for all monthly data sets and in both major directions. The semi-diurnal periodicities may be due to the tidal motions. The 5.2 h and 3.2 h are the first and second modes of free oscillations of Lake Ontario (Rao and Schwab, 1974 and Palmer and Poulton, 1976). At the bottom location 1102 in Burlington Canal, longer periods of 24.0, 20.0 and 10.9 h were observed. The periodicities of the Burlington Canal indicate that the currents are largely affected by tidal motions and first and second modes of free oscillations of Lake Ontario.

Summary of 95% significant coherences is presented in Table 10 for Burlington Canal water movements and temperatures at 3 levels (locations 1101, 1116 and 1117) during June to August 1976. Significant coherences between current speed and water temperatures at the same location were generally present between 2.0 and 17.1 h. Current speed between two locations exhibited coherences from 12.0 to 30.0 h. Coherence for water temperature between two levels ranged from 2.3 to 24.0 h. These significant coherences between water currents and temperatures at any two levels indicate the vertical cross-correlations of currents and temperature in Burlington Canal during June to August 1976. It is not known if such vertical homogeneity of currents and water temperature existed during the same period of other years.

DESJARDINS CANAL

Table 11 summarizes the major spectral periods in Desjardins Canal from June to November 1976. The most commonly occurring periodicities in this canal are 12.0, 5.2 and 3.2 h. The 12.0 h period is due to the tidal motions. The other two periods are the first and second modes of free oscillations of Lake Ontario. In November 1976, a 13.3 h period was observed along the channel direction; this may be due to the lake-wide seiches.

It is interesting to note that the Burlington and Desjardins Canals have similar periodic motions, namely the tidal motions and the first two modes of free oscillations of Lake Ontario. Therefore, the water movements in the two canals were caused by the same phenomena.

WATER TEMPERATURE

HAMILTON HARBOUR

At the mid-harbour location (1104), water temperatures were measured from June to August 1976. The mean water temperatures varied from 17.6 to 19.2°C, progressively increasing from June to August (see Table 12). The standard deviation of the temperature decreased from 1.1°C in June to 0.6°C in August 1976. The minimum recorded temperature during a month increased from 14.3 to 16.7°C, while the maximum recorded temperature during a month remained almost constant at 20°C.

BURLINGTON CANAL

Table 13 presents the frequency of occurrence of water temperatures in Burlington Canal during 1976-77. At the top location 1117, mean temperatures varied from 6.6 to 20.9°C with standard deviations ranging between 1.4 and 2.4°C from June to November 1976. At the next location down (1116), from June to August 1976 and May to July, 1977, the mean temperature ranged between 15.2 and 19.7°C, with the standard deviations from 1.4 to 2.6°C. The mean temperature varied from 6.6 to 19.3°C, with the standard deviation ranging from 1.2 to 2.7°C at the mooring 1101, from June to November 1976 and May to July, 1977. During June and July 1976, at the lowest site 1101, the mean water temperatures were 11.0 and 9.7°C, with standard deviations of 2.4 and 2.9°C respectively. Figure 5 presents the mean temperature graphs for June and July of 1976 and 1977, at 3 levels. The figure shows a very sharp decline in mean temperature with depth during 1977, compared to the 1976 curve.

DESJARDINS CANAL

Mean water temperature in Desjardins Canal from May to November 76 varied from 4.5 to 20.8°C (see Table 14), while the standard deviations ranged from 1.0 to 3.5°C. The maximum temperature recorded in the canal was 26.9°C during the study period. As the canal is generally shallow, with a maximum depth of 3.7 m, isothermal conditions are expected to prevail. No bathythermographs were taken to support the assumption of isothermal regime.

CONCLUSIONS

The currents at the mid-harbour location during 1976-77 were similar to those observed during 1975. The resultant currents varied from 0.7 to 1.8 $cm.s^{-1}$ while the arithmetic average speed ranged from 1.7 to 4.8 $cm.s^{-1}$. In Burlington Canal, the resultant currents varied from 0.6 to 13.4 $cm.s^{-1}$, while the arithmetic average speed ranged between 6.9 and 16.7 $cm.s^{-1}$. The maximum speed recorded in Burlington Canal during 1976-77 was 129 $cm.s^{-1}$. During 1976 the resultant currents in Desjardins Canal varied from 3.3 to 8.1 $cm.s^{-1}$, while the arithmetic average speed ranged between 9.8 and 24.2 $cm.s^{-1}$. Both canals exhibited relatively faster currents compared to mid-harbour and lake coastal currents, probably due to the constrictions.

Net flow through Burlington Canal was estimated as 0.2 to 1.4% of the harbour volume per day, while the total exchange through the canal ranged from 1.2 to 1.6% of the harbour volume per day. Net flow through Desjardins Canal to Hamilton Harbour was estimated as 0.02 to 0.05% of the harbour volume per day, while the total exchange through the canal varied from 0.07 to 0.15% of the harbour volume per day. The exchange through the Burlington Canal was an order of magnitude larger than through Desjardins Canal.

Diurnal and semi-diurnal motions were observed at the mid-harbour location. Lake-wide seiches and modes of free oscillations of Lake Ontario were also present, indicating the influence of Lake Ontario at the harbour location. Both Burlington and Desjardins Canals exhibited the semi-diurnal periodicities, as well as the first two modes of free oscillations of Lake Ontario. Thus, the tidal motions and lake effects appear to influence the water movements in the two canals. Significant coherences were observed from 2 to 30 h between different levels in Burlington Canal during June to August 1976, indicating vertical cross-correlations of currents and water temperatures in the canal.

Mean water temperatures in Hamilton Harbour varied from 17.6 to 19.2°C during June to August 1976. The maximum temperature recorded at this location was 20°C. In Burlington Canal, the mean water temperatures varied from 6.6 to 20.9°C from June to November 1976, and May to July 1977, with the standard deviations of 1.2 to 2.7°C. The Canal had a weak stratification during summer 1976 and a strong stratification during summer 1977. No stratification was observed in the canal from October to November 1976. In Desjardins Canal, from May to November 1976, the mean temperature varied from 4.5 to 20.8°C, while the standard deviations ranged from 1.0 to 3.5°C. Isothermal regime was assumed in the canal.

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TABLE 1: Current Instrument Operations in Burlington and Desjardins Canals and Hamilton Harbour, Lake Ontario 1976-77

Location	Location Code	Instrument		Instrument from Bottom (m)	Total Water Depth (m)	Period of Operation	
		Type	No.			From	To
Burlington Canal	1117	P*	239	8.5	9.4	3 Jun 76	23 Aug 76
		P	239	8.5	9.4	2 Oct 76	25 Nov 76
		P	164	8.5	9.4	31 May 77	20 Jul 77
Burlington Canal	1116	P	189	7.5	9.4	3 Jun 76	23 Aug 77
		P	144	7.5	9.4	1 Oct 76	25 Nov 77
		P	206	7.5	9.4	28 May 77	22 Jul 77
Burlington Canal	1101	P	206	6.1	9.4	3 Jun 76	23 Aug 76
		P	206	6.1	9.4	1 Oct 76	25 Nov 76
		P	239	6.1	9.4	28 May 77	22 Jul 77
Burlington Canal	1102	P	207	2.1	9.4	3 Jun 76	10 Jul 76
Hamilton Harbour	1104	G**	038	16.3	22.9	9 Jun 76	23 Aug 76
		G	278	16.3	22.9	28 May 77	27 Aug 77
Desjardins Canal	1109	G	039	1.9	3.7	27 May 76	23 Aug 76
		G	025	1.9	3.7	4 Sep 76	24 Nov 76

* Plessey

** Geodyne

TABLE 2: Statistical Summary of Current Meter Operations
Hamilton Harbour, Lake Ontario, 1976-77

LOCATION CODE 1104

	Jun 76	Jul 76	Aug 76	May 77	Jun 77	Jul 77	Aug 77
Resultant direction coming from 0^o as North	24	5	338	52	357	319	345
Resultant speed ($cm.s^{-1}$)	0.87	1.77	1.26	0.27	0.67	0.72	0.78
Average speed ($cm.s^{-1}$)	4.82	4.60	3.73	2.38	1.67	2.05	2.35
Maximum speed ($cm.s^{-1}$)	15	16	10	11	9	28	18
Persistence factor	0.18	0.38	0.34	0.11	0.40	0.35	0.33
Percentage of negligible* speed (% of recording period)	0	0	0	17	25	17	11
Percentage of time going in direction of resultant	13	19	21	11	23	21	15
Total number of readings	3168	4463	3241	576	4320	4464	3785
Interval of readings (min)	10	10	10	10	10	10	10

*$< 0.30\ cm.s^{-1}$

TABLE 3: Statistical Summary of Current Meter Operations
Burlington Canal, Lake Ontario, 1976-77

LOCATION CODE 1117

	Jun 76	Jul 76	Aug 76	Oct 76	Nov 76	May 77	Jun 77	Jul 77
Resultant direction coming from 0^o as North	257	258	261	255	220	255	259	257
Resultant speed ($cm.s^{-1}$)	8.63	11.58	6.77	4.85	0.93	5.11	10.91	13.38
Average speed ($cm.s^{-1}$)	13.45	13.69	10.29	12.03	9.83	7.62	13.35	16.72
Maximum speed ($cm.s^{-1}$)	83	54	48	75	49	25	68	71
Persistence factor	0.64	0.85	0.66	0.40	0.09	0.67	0.82	0.80
Percentage of negligible* speed (% of recording period)	1	0	0	1	1	0	0	0
Percentage of time going in direction of resultant	69	81	68	56	4	64	80	79
Percentage of time going towards lake	69	81	68	56	45	64	80	79
Mean speed towards lake ($cm.s^{-1}$)	18.88	21.31	15.38	18.13	12.68	8.44	19.30	27.43
Percentage of time going towards harbour	20	11	21	28	37	8	11	13
Mean speed towards harbour ($cm.s^{-1}$)	11.55	8.74	8.16	14.37	13.74	8.61	9.36	13.07
Total number of readings	4032	4464	3189	4320	3478	144	4320	2749
Interval of readings (min)	10	10	10	10	10	10	10	10

* < 0.30 $cm.s^{-1}$

TABLE 3 (cont'd.)

LOCATION CODE 1116

	Jun 76	Jul 76	Aug 76	Oct 76	Nov 76	May 77	Jun 77	Jul 77
Resultant direction coming from 0° as North	263	266	265	241	226	250	256	255
Resultant speed ($cm.s^{-1}$)	5.01	5.94	3.56	3.66	2.26	4.03	6.80	6.84
Average speed ($cm.s^{-1}$)	11.89	9.34	7.78	10.48	10.39	14.73	11.70	13.16
Maximum speed ($cm.s^{-1}$)	129	56	48	77	52	116	72	76
Persistence factor	0.42	0.64	0.46	0.35	0.22	0.27	0.58	0.52
Percentage of negligible* speed (% of recording period)	1	5	2	2	1	0	0	0
Percentage of time going in direction of resultant	57	65	54	46	43	51	64	60
Percentage of time going towards lake	57	65	54	46	43	51	64	60
Mean speed towards lake ($cm.s^{-1}$)	15.47	14.88	11.96	15.06	16.29	17.96	16.95	18.26
Percentage of time going towards harbour	29	21	24	32	43	31	21	24
Mean speed towards harbour ($cm.^{-1}$)	11.75	8.12	8.45	10.31	11.71	17.63	10.83	12.13
Total number of readings	4032	4404	3239	4464	3528	576	4320	3046
Interval of readings (min)	10	10	10	10	10	10	10	10

* < 0.30 cm.s-1

TABLE 3 (cont'd.)

LOCATION CODE 1101

	Jun 76	Jul 76	Aug 76	Oct 76	Nov 76	May 77	Jun 77	Jul 77
Resultant direction coming from 0^o as North	258	261	271	261	259	48	45	44
Resultant speed ($cm.s^{-1}$)	0.95	0.61	1.01	2.55	1.55	3.66	7.56	5.54
Average speed ($cm.s^{-1}$)	10.48	6.91	7.06	10.73	10.78	14.08	10.78	7.36
Maximum speed ($cm.s^{-1}$)	125.98	49.91	44.06	79.02	50.14	110.79	63.98	50.52
Persistence factor	0.09	0.09	0.14	0.24	0.14	0.26	0.70	0.75
Percentage of negligible* speed (% of recording period)	1	4	2	2	1	0	1	10
Percent of time going in direction of resultant	39	41	44	50	47	57	75	76
Percentage of time going towards lake	39	41	44	50	47	30	17	14
Mean speed towards lake ($cm.s^{-1}$)	13.75	9.50	9.6	14.28	15.26	18.58	9.55	7.30
Percentage of time going towards harbour	40	40	39	34	40	57	75	76
Mean speed towards harbour ($cm.s^{-1}$)	11.28	8.42	8.02	11.49	13.00	16.49	13.89	10.56
Total number of readings	4032	4464	3190	4464	3478	576	4320	3049
Interval of readings (min)	10	10	10	10	10	10	10	10

* < 0.30 $cm.s^{-1}$

TABLE 3: (cont'd.)

LOCATION CODE 1102

	Jun 76	Jul 76
Resultant direction coming from 0^o as North	290	338
Resultant speed	0.54	0.47
Average speed	0.62	0.73
Maximum speed	24.59	2.96
Persistence factor	0.88	0.65
Percentage of negligible* speed (% of recording period)	49	30
Percent of time going in direction of resultant	52	26
Percent of tim going towards lake	52	19
Mean speed towards lake ($cm.s^{-1}$)	0.76	0.93
Percent of time going towards harbour	6	5
Mean speed towards harbour ($cm.s^{-1}$)	0.72	0.43
Total number of readings	4032	1367
Interval of readings (min)	10	10

$* < 0.30\ cm.s^{-1}$

TABLE 4: Flow Through Burlington Canal, Lake Ontario, 1976[2]

	Average Flow Into Harbour			Average Flow Into Lake			Total Exchange			Net Exchange Toward The Lake		
PERIOD	x 10^6 $m^3.d^{-1}$	$m^3.s^{-1}$	% of Harbour Vol/day	x 10^6 $m^3.d^{-1}$	$m^3.s^{-1}$	% of Harbour Vol/day	x 10^6 $m^3.d^{-1}$	$m^3.s^{-1}$	% of Harbour Vol/day	x 10^6 $m^3.d^{-1}$	$m^3.s^{-1}$	% of Harbour Vol/day
Jun	0.80	9.26	0.29	3.68	42.59	1.31	4.48	51.85	1.60	2.88	33.33	1.02
Jul	0.14	1.62	0.05	3.99	46.18	1.43	4.13	47.80	1.48	3.85	44.56	1.38
Aug	0.37	4.28	0.13	2.72	31.48	0.97	3.09	35.76	1.10	2.35	27.20	0.84
Oct	0.93	10.76	0.33	2.74	31.71	0.99	3.67	42.47	1.32	1.81	20.95	0.66
Nov	1.44	16.67	0.51	1.95	22.57	0.70	3.39	39.24	1.21	0.51	5.90	0.19

[2] There is a discrepancy, as yet unresolved, between the exchange flows in this table, calculated by the excursion-episode method (Kohli, 1979) and those deduced indirectly from their flows to the harbour and the water level changes in the harbour, as presented in Section H, Volume II of this report. To resolve this discrepancy, a more refined water budget will be calculated for the period spring, 1979 to spring, 1980. The results will be compared with the exchange flows calculated for the same period by the excursion-episode method.

TABLE 5: Comparison of Flow Through Burlington Canal

(Flow x 10^6 $m^3.d^{-1}$)

Flow through Burlington Canal	Harris et al (1979) (1)	Kohli (1979) 1975 Data (2)	Mean Value of Present Study 1976 Data (3)	Mean of Columns 2&3 (4)	Ratio Col.1/Col.4 (5)
To lake Q_1	6.08	2.04	3.02	2.53	2.4
To harbour Q_2	5.30	0.69	0.74	0.72	7.4
Total $Q = Q_1 + Q_2$	11.38	2.73	3.76	3.25	3.5
Net $q = Q_1 - Q_2$ towards the lake	0.78	1.35	2.28	1.82	0.4

TABLE 6: Statistical Summary of Current Meter Operations, Desjardins Canal, Hamilton Harbour, Lake Ontario 1976

LOCATION CODE 1109

	May	Jun	Jul	Aug	Sep	Oct	Nov
Resultant direction coming from 0^o as North	264	278	269	278	272	273	266
Resultant speed ($cm.s^{-1}$)	3.28	4.25	3.56	3.37	13.71	8.05	6.73
Average speed ($cm.s^{-1}$)	9.83	21.13	14.27	16.69	24.17	21.76	23.72
Maximum speed ($cm.s^{-1}$)	48.57	87.91	69.36	65.48	85.23	79.24	70.25
Persistence factor	0.33	0.20	0.25	0.20	0.57	0.37	0.28
Percentage of negligible* speed (% of recording period)	0	0	0	0	0	0	0
Percentage of time going in direction of resultant	46	41	42	42	33	36	41
Percentage of time going towards Cootes Paradise	46	41	42	42	28	36	41
Mean Speed towards Cootes Paradise ($cm.s^{-1}$)	15.63	31.54	22.64	24.84	25.73	35.18	34.00
Percentage of time going toward harbour	31	32	33	33	11	20	25
Mean Speed towards harbour ($cm.s^{-1}$)	11.87	25.53	16.24	19.17	24.93	30.0	30.26
Total number of readings	721	4320	4464	3232	3892	4467	3386
Interval of readings (min)	10	10	10	10	10	10	10

* < 0.30 $cm.s^{-1}$

Cross-sectional Area of Desjardins Canal = 57 m^2

TABLE 7: Flow Through Desjardins Canal, Hamilton Harbour, Lake Ontario, 1976

Period 1976	Average Flow Into Cootes Paradise			Average Flow Into Harbour			Total Exchange			Net Exchange Towards Harbour		
	x 10^6 $m^3.d^{-1}$	$m^3.s^{-1}$	% of Harbour Vol/day	x 10^6 $m^3.d^{-1}$	$m^3.s^{-1}$	% of Harbour Vol/day	x 10^6 $m^3.d^{-1}$	$m^3.s^{-1}$	% of Harbour Vol/day	x 10^6 $m^3.d^{-1}$	$m^3.s^{-1}$	% of Harbour Vol/day
May	0.07	0.84	0.03	0.14	1.64	0.05	0.21	2.48	0.08	0.07	0.80	0.02
Jun	0.16	1.87	0.06	0.26	2.95	0.09	0.42	4.82	0.15	0.10	1.08	0.03
Jul	0.11	1.22	0.04	0.19	2.17	0.07	0.30	3.39	0.11	0.08	0.95	0.03
Aug	0.12	1.45	0.04	0.21	2.38	0.08	0.33	3.83	0.12	0.09	0.93	0.04
Sep	0.06	0.63	0.02	0.14	1.65	0.05	0.20	2.28	0.07	0.08	1.02	0.03
Oct	0.12	1.37	0.04	0.25	2.89	0.09	0.37	4.26	0.13	0.13	1.52	0.05
Nov	0.15	1.73	0.05	0.27	3.18	0.10	0.42	4.91	0.15	0.12	1.45	0.05

TABLE 8: Summary of Major Spectral Periods (Hours)
Hamilton Harbour, Lake Ontario, 1976-77

(95 Percent Confidence Level)

LOCATION	PERIOD	NORTH-SOUTH	EAST-WEST
1104	Jun 76	12.0*	None
	Jul 76	None	24.0, 12.0, 6.0*
	Aug 76	17.1*, 6.0*, 4.8*, 4.3*	None
	Jun 77	20.0*, 10.0*, 3.4*	4.6*, 3.6*
	Jul 77	12.0	None
	Aug 77	None	13.3*

* 80 Percent confidence level

TABLE 9: Summary of Major Spectral Periods (Hours)
Burlington Canal, Lake Ontario 1976-77

(95% Confidence Level)

LOCATION	PERIOD	ALONG CHANNEL	ACROSS CHANNEL
1117	Jun 76	12.0, 5.2, 3.2	12.0, 5.2, 3.2
	Jul 76	12.0, 5.2, 3.2*	12.0, 5.2
	Aug 76	5.2, 3.2*	12.0, 5.2, 3.2
	Oct 76	12.0*, 5.2, 3.2	12.0, 5.2, 3.2
	Nov 76	12.0, 5.2, 3.4*	12.0, 5.2, 3.5*
	Jun 77	12.0, 5.2, 3.2	12.0, 5.2, 3.2
	Jul 77	12.0, 5.2, 3.4	12.0, 5.2, 3.4
1116	Jun 76	12.0*, 5.0, 3.2*	12.0*, 5.2, 3.2*
	Jul 76	12.0, 5.2	12.0, 5.2, 3.2*
	Aug 76	12.0, 5.2, 3.2*	12.0, 5.2, 3.2*
	Oct 76	12.0, 5.2, 3.2	12.0, 5.2, 3.2
	Nov 76	12.0, 5.2, 3.2*	12.0, 6.7*, 5.2, 3.4*
	Jun 77	20.0*, 12.0, 8.0*, 5.2*, 3.2	12.0*, 8.0*, 5.5*, 3.2*
	Jul 77	13.3, 5.2	20.0*, 12.0*, 5.5*
1101	Jun 76	12.0*, 5.2, 3.2*	12.0*, 12.0*, 5.5*
	Jul 76	12.0, 5.2, 3.2*	12.0, 5.2
	Aug 76	12.0, 5.2, 3.2*	12.0, 5.2, 3.2*
	Oct 76	12.0, 5.2, 3.2*	12.0*, 5.2, 3.2*
	Nov 76	12.0, 5.2, 3.2*	12.0, 5.2, 3.2*
	Jun 77	12.0*, 6.0*, 5.2	12.0, 5.2
	Jul 77	12.0*	12.0*, 5.2*
1102	Jun 76	5.2*, 4.8	5.2*
	Jul 76	20.0*	24.0*, 10.9*

* 80 Percent Confidence Level

TABLE 10: Summary of Coherences (95% Confidence) Burlington Canal, Lake Ontario, 1976

(Hours)

	JUNE		JULY		AUGUST	
Location #1 Location #2	1116 1117	1101 1117	1116 1117	1101 1117	1116 1117	1101 1117
Speed along the canal and Water Temp. at #2	2.0, 2.7 to 6.0, 10.9 to 13.3, 17.1	2.7 to 3.4, 3.7 to 7.1, 9.2 to 17.1	2.9 to 3.2, 3.7 to 4.0, 4.3 to 6.3, 7.1, 10.9 to 17.1	2.4, 2.9 to 3.3, 3.6 to 6.3, 8.6 to 9.2, 0.9 to 17.1	2.1, 3.0-3.2, 4.0, 4.3, 4.4	2.2, 2.7 to 2.9, 3.4, 3.9 to 4.6, 5.0 to 6.3, 15.0
Speed across the canal and Water Temp. at #2	2.0, 2.7 to 6.0, 9.2, 10.9 to 13.3	2.7 to 3.3, 3.7 to 6.0, 6.7 to 7.1, 10.9 to 13.3, 17.1	2.3, 2.9 to 3.3, 3.7 to 4.0, 4.3 to 6.0, 7.1, 10.9 to 17.1	2.4, 2.9 to 3.3, 3.6 to 5.7, 8.6 to 9.2, 10.9 to 15.0	2.1, 3.0 to 3.2, 4.0, 4.4, 5.7	2.2, 2.6, 3.9 to 4.1, 4.4, 5.2 to 6.3, 7.5 to 8.5
Speed along the canal and Water Temp. at #1	3.1 to 3.3, 4.0 to 5.7, 7.1, 12.0 to 17.1	3.1 to 3.4, 4.0 to 5.7, 7.1, 12.0 to 17.1	2.3, 2.6, 2.7 to 2.9, 3.7 to 4.0, 4.4 to 5.0, 6.0, 7.1, 15.0 to 20.0	2.3, 2.6, 2.7 to 2.9, 4.0, 4.4 to 5.0, 6.0, 7.1, 15.0 to 20.0	2.9 to 3.1, 4.8 to 5.2, 6.0 to 6.3, 17.1	3.0, 3.1, 4.8 to 5.2, 6.0 to 6.3, 17.1
Speed across the canal and Water Temp. at #1	3.0 to 3.3, 3.9 to 6.0, 7.1, 12.0 to 17.1	3.1 to 3.3, 3.9 to 6.0, 7.1, 12.0 to 17.1	2.7 to 2.9, 3.9, 4.4 to 5.0, 5.7 to 6.0, 7.1, 13.3 to 17.1	2.7 to 2.9, 3.9, 4.4 to 5.0, 5.7 to 6.0, 7.1, 13.3 to 17.1	3.0, 3.1, 4.8 to 5.2, 6.0 to 6.3, 17.1	3.0, 3.1, 4.8 to 5.2, 6.0 to 6.3, 17.1
Speed along the canal at #2 and #1	2.1 to 8.0, 9.2, 10.9 to 15.0	2.1 to 6.7, 7.5, 10.4 to 13.3	2.2 to 9.2, 10.9 to 30.0	2.0 to 2.6, 2.7 to 6.7, 8.0 to 9.2, 10.9 to 13.3, 24.0	2.0 to 2.3, 2.7 to 9.2, 10.9 to 15.0, 24.0	2.2, 2.7 to 13.3
Speed across the canal at #2 and #1	2.2 to 8.0, 10.9 to 10.9 to 13.3	2.3 to 6.0, 7.5, 10.9 to 13.3	2.2, 2.3 to 9.2, 10.9 to 13.3, 20.0 to 30.0	2.0 to 2.5, 2.8 to 6.7, 10.9 to 13.3	2.1, 2.2, 2.7 to 6.3, 10.9 to 17.1	2.0, 2.2, 2.7 to 13.3
Water Temp.* at #2 and #1	2.3 to 120.0	2.3, 2.8, 3.0 to 7.1, 9.2 to 13.3	3.2, 3.9 to 4.8, 5.5 to 6.7, 10.0 to 24.0	4.0 to 4.8, 5.2 to 6.0, 17.1 to 20.0	2.7, 2.8, 3.0 to 3.2, 3.5, 3.6, 5.5, 7.1 to 7.5, 10.0 to 13.3	7.1 to 7.5

* Water temperature less its grand mean.

TABLE 11: Summary of Major Spectral Periods (Hours)
Desjardin Canal,
Hamilton Harbour, Lake Ontario 1976

(95% Confidence Level)

LOCATION	PERIOD	ALONG CHANNEL	ACROSS CHANNEL
1109	Jun 76	12.0, 5.0	12.0, 5.0
	Jul 76	12.0, 5.2	12.0, 6.0*, 5.2, 3.2*
	Aug 76	12.0, 5.2, 3.2*	12.0, 5.2, 3.5*, 3.2
	Sep 76	12.0*, 6.3*, 4.8	12.0*, 5.2
	Oct 76	12.0, 5.2, 3.3*	12.0, 5.2, 3.3*
	Nov 76	13.3*, 5.2	12.0, 5.2

* 80 Percent Confidence Level

TABLE 12: Temperature Frequency,
Hamilton Harbour, Lake Ontario 1976
Percentage of Occurrence
Location Code 1104

Temperature Range °C	Jun 76	Jul 76	Aug 76
14.0 - 14.9	3.05		
15.0 - 15.9	6.68	0.14	
16.0 - 16.9	11.45	16.78	0.19
17.0 - 17.9	43.51	53.59	4.89
18.0 - 18.9	26.15	23.41	29.32
19.0 - 19.9	8.97	6.09	61.28
20.0 - 20.9	0.19		4.32
TOTAL	100.0	100.0	100.0
Mean °C	17.61	17.67	19.16
Std. Dev. °C	1.08	0.74	0.57
Minimum °C	14.28	15.64	16.74
Maximum °C	20.17	19.82	20.31
Series Length (h)	528	743	540

TABLE 13: Temperature Frequency, Burlington Canal, Lake Ontario, 1976-77

Percentage of Occurrence

Temperature Range °C	LOCATION										
	1117					1116					
	PERIOD										
	Jun 76	Jul 76	Aug 76	Oct 76	Nov 76	Jun 76	Jul 76	Aug 76	May 77	Jun 77	Jul 77
3.0- 3.9					1.04						
4.0- 4.9					19.13						
5.0- 5.9				0.28	19.13						
6.0- 6.9				0.56	20.70				1.05		
7.0- 7.9				1.97	16.17	0.30			0.00		
8.0- 8.9				4.65	13.04	0.00			0.00		0.20
9.0- 9.9				14.79	9.91	0.15			1.05		0.00
10.0-10.9	0.30			13.94	0.87	0.30	0.14		4.21		0.00
11.0-11.9	0.61			6.20		0.45	0.00		7.37		0.20
12.0-12.9	0.15			11.13		2.56	0.00		3.16	0.14	0.00
13.0-13.9	0.76			11.13		5.86	0.27		5.26	0.84	0.40
14.0-14.9	2.42			19.44		8.12	1.09		18.95	2.38	0.99
15.0-15.9	7.26			13.24		9.32	5.70	0.37	35.79	17.95	2.19
16.0-16.9	6.20	1.90	0.95	2.68		13.68	10.45	2.06	2.11	23.70	7.75
17.0-17.9	10.29	3.39	3.80			18.05	22.25	9.72	3.16	15.71	11.53
18.0-18.9	13.16	11.94	8.56			18.35	24.69	21.68	5.26	9.82	14.31
19.0-19.9	22.09	21.17	15.40			12.18	24.97	22.06	9.47	14.03	14.91
20.0-20.9	18.76	33.24	20.34			8.57	8.68	29.16	3.16	9.54	15.71
21.0-21.9	14.07	19.95	31.94			2.11	1.63	9.91		4.35	18.89
22.0-22.9	3.93	5.29	8.37				0.14	4.86		1.54	9.15
23.0-23.9		3.12	5.89					0.19			2.78
24.0-24.9			4.37								0.99
25.0-100.0			0.38								
TOTAL	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Mean °C	19.02	20.29	20.90	12.35	6.62	17.25	18.29	19.66	15.22	17.68	19.63
St. Dev. °C	2.16	1.36	1.66	2.44	1.63	2.26	1.48	1.38	2.64	1.95	2.16
Minimum °C	10.41	16.18	16.78	5.96	3.82	7.16	10.04	15.65	6.85	12.45	8.60
Maximum °C	22.87	23.74	25.20	16.98	10.23	21.63	22.20	23.03	20.80	22.99	24.65
Series Length (h)	672	744	531	720	579	672	744	539	96	720	507

TABLE 13: (cont'd)

Percentage of Occurrence

Temperature Range °C	LOCATION									
	1101								1102	
	PERIOD									
	Jun 76	Jul 76	Aug 76	Oct 76	Nov 76	May 77	Jun 77	Jul 77	Jun 76	Jul 76
3.0- 3.9					0.87					
4.0- 4.9					17.57					
5.0- 5.9				0.14	19.13		0.28	1.79		3.11
6.0- 6.9				1.36	23.65	5.26	3.65	9.16	2.87	9.78
7.0- 7.9	0.30			2.99	16.87	9.47	15.43	11.16	10.11	17.78
8.0- 8.9	0.15	0.14		5.83	12.87	6.32	23.98	16.93	11.01	17.78
9.0- 9.9	0.30	0.14		15.74	8.17	17.89	22.58	14.54	10.26	20.89
10.0-10.9	0.60	0.27		12.08	0.87	10.53	9.82	15.74	16.74	11.11
11.0-11.9	2.39	0.54		7.46		15.79	7.15	8.17	13.27	3.11
12.0-12.9	3.59	1.09		12.08		14.74	7.15	3.98	12.67	3.56
13.0-13.9	8.37	4.07		14.79		16.84	4.35	2.79	9.20	2.22
14.0-14.9	11.06	10.85		22.66		3.16	3.23	8.96	10.26	0.44
15.0-15.9	17.49	15.20	0.19	4.48			1.54	3.98	2.41	1.33
16.0-16.9	18.98	25.24	1.73	0.41			0.56	2.39	0.45	7.11
17.0-17.9	19.58	24.15	13.85				0.14	0.20	0.15	0.89
18.0-18.9	8.52	10.99	25.19				0.14	0.00	0.30	0.00
19.0-19.9	4.78	5.97	29.42					0.20	0.30	0.89
20.0-20.9	3.14	1.36	22.12							
21.0-21.9	0.75		7.12							
22.0-22.9			0.38							
23.0-23.9										
24.0-24.9										
25.0-25.9										
TOTAL	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Mean °C	16.16	16.57	19.25	11.99	6.62	10.75	9.76	10.20	11.03	9.69
Std. Dev. °C	2.16	1.69	1.20	2.34	1.54	2.17	2.16	2.74	2.42	2.94
Minimum °C	7.44	8.90	15.38	5.98	3.90	6.41	5.88	5.04	6.33	5.53
Maximum °C	21.49	20.58	22.13	16.33	10.29	14.21	18.36	19.55	19.43	19.38
Series Length (h)	672	744	531	744	579	96	720	508	672	227

TABLE 14: Temperature Frequency, Desjardins Canal Hamilton Harbour, Lake Ontario 1976
Percentage of Occurrence

Temperature Range °C	May 76	Jun 76	Jul 76	Sep 76	Oct 76	Nov 76
0.0 - 0.9						2.68
1.0 - 1.9						6.26
2.0 - 2.9					0.94	9.48
3.0 - 3.9					0.94	19.32
4.0 - 4.9					1.75	22.36
5.0 - 5.9					3.51	18.96
6.0 - 6.9					7.96	11.27
7.0 - 7.9			0.14		8.10	7.87
8.0 - 8.9		0.28	0.00		8.64	1.79
9.0 - 9.9		0.00	0.00		6.34	
10.0 - 10.9		0.00	0.00		8.37	
11.0 - 11.9		0.70	0.00	0.16	9.85	
12.0 - 12.9		0.42	0.54	3.89	11.74	
13.0 - 13.9		0.56	0.14	12.31	6.88	
14.0 - 14.9	1.69	1.26	2.71	13.86	9.18	
15.0 - 15.9	7.63	4.63	3.39	7.01	9.04	
16.0 - 16.9	6.78	9.55	6.50	4.98	6.07	
17.0 - 17.9	43.22	12.22	10.57	13.24	0.67	
18.0 - 18.9	37.29	14.61	11.92	19.16		
19.0 - 19.9	2.54	16.25	14.09	16.98		
20.0 - 20.9	0.85	19.52	10.57	7.17		
21.0 - 21.9		7.87	10.30	1.25		
22.0 - 22.9		7.30	4.61			
23.0 - 23.9		1.83	1.63			
24.0 - 24.9		0.28	0.41			
25.0 - 25.9		0.14	0.14			
26.0 - 26.9		2.67	22.36			
TOTAL	100.0	100.0	100.0	100.0	100.0	100.0
Mean °C	17.68	19.29	20.84	16.95	11.07	4.54
Std. Dev. °C	0.99	2.59	3.81	2.44	3.47	1.76
Minimum °C	14.67	8.15	7.00	11.77	2.28	0.12
Maximum °C	20.12	26.90	26.90	21.44	17.47	8.50
Series Length (h)	120	720	744	648	744	564

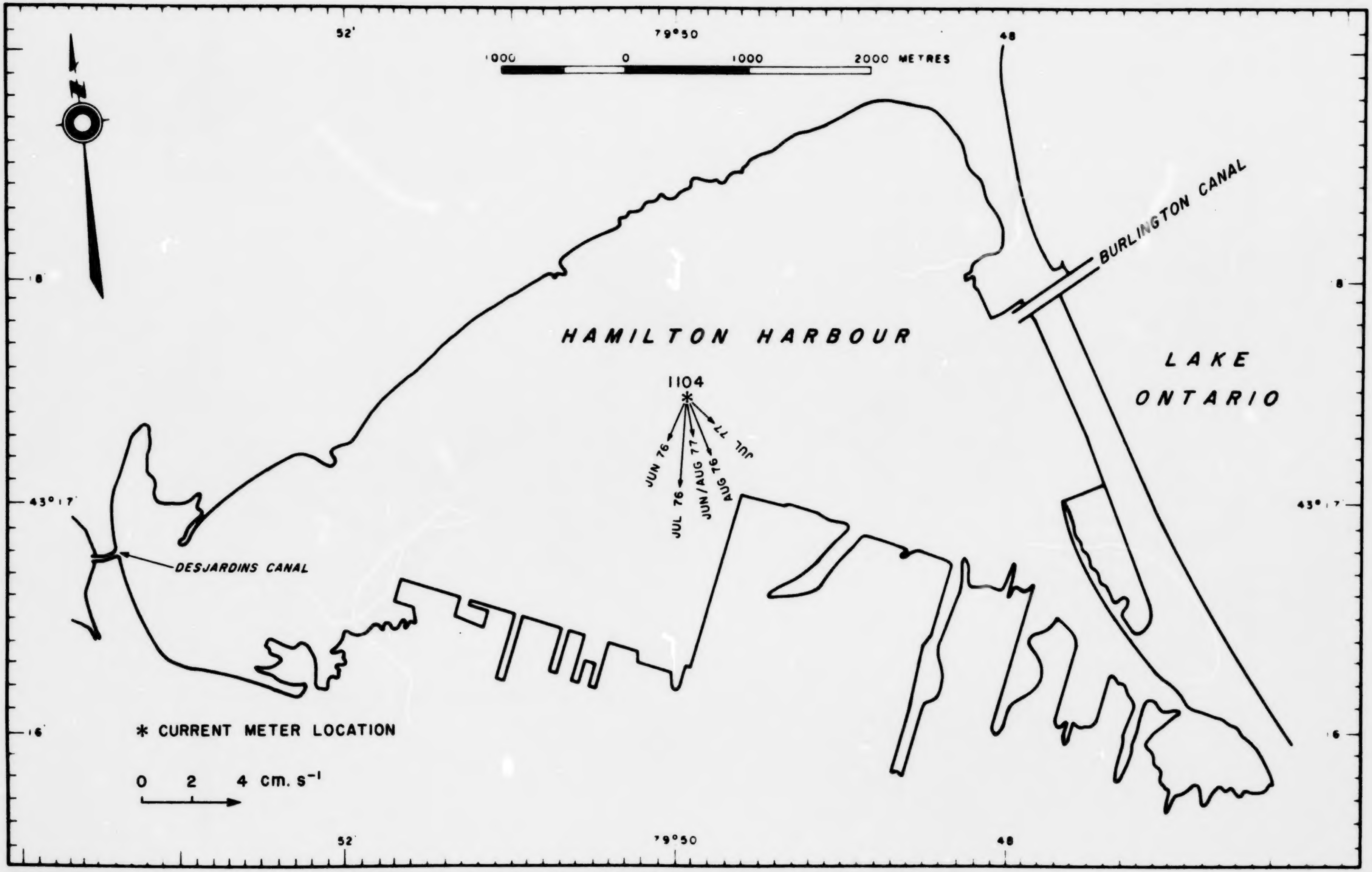
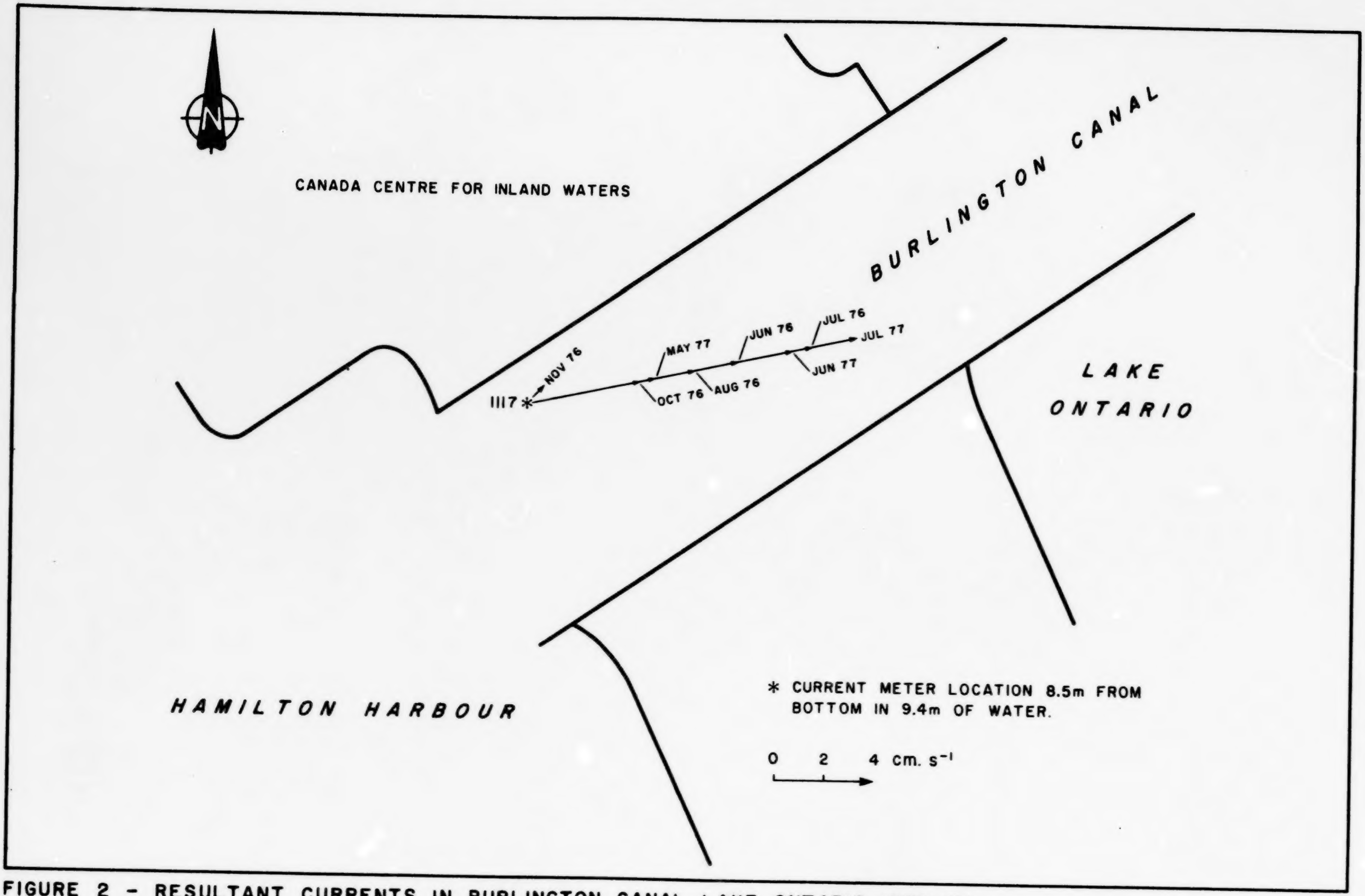

52'
79°50
48
1000
0
1000
2000 METRES
18
43°17
16
BURLINGTON CANAL
HAMILTON HARBOUR
LAKE ONTARIO
1104
JUN 76
JUL 76
JUN/AUG 77
AUG 76
JUL 77
DESJARDINS CANAL
* CURRENT METER LOCATION
0 2 4 cm. s⁻¹

FIGURE 1 - RESULTANT CURRENTS IN HAMILTON HARBOUR, LAKE ONTARIO, 1976-77.


CANADA CENTRE FOR INLAND WATERS
BURLINGTON CANAL
LAKE ONTARIO
HAMILTON HARBOUR
1117
NOV 76
MAY 77
OCT 76
AUG 76
JUN 76
JUL 76
JUN 77
JUL 77
N
0
2
4 cm. s⁻¹

* CURRENT METER LOCATION 8.5m FROM BOTTOM IN 9.4m OF WATER.

FIGURE 2 - RESULTANT CURRENTS IN BURLINGTON CANAL, LAKE ONTARIO, 1976-77.

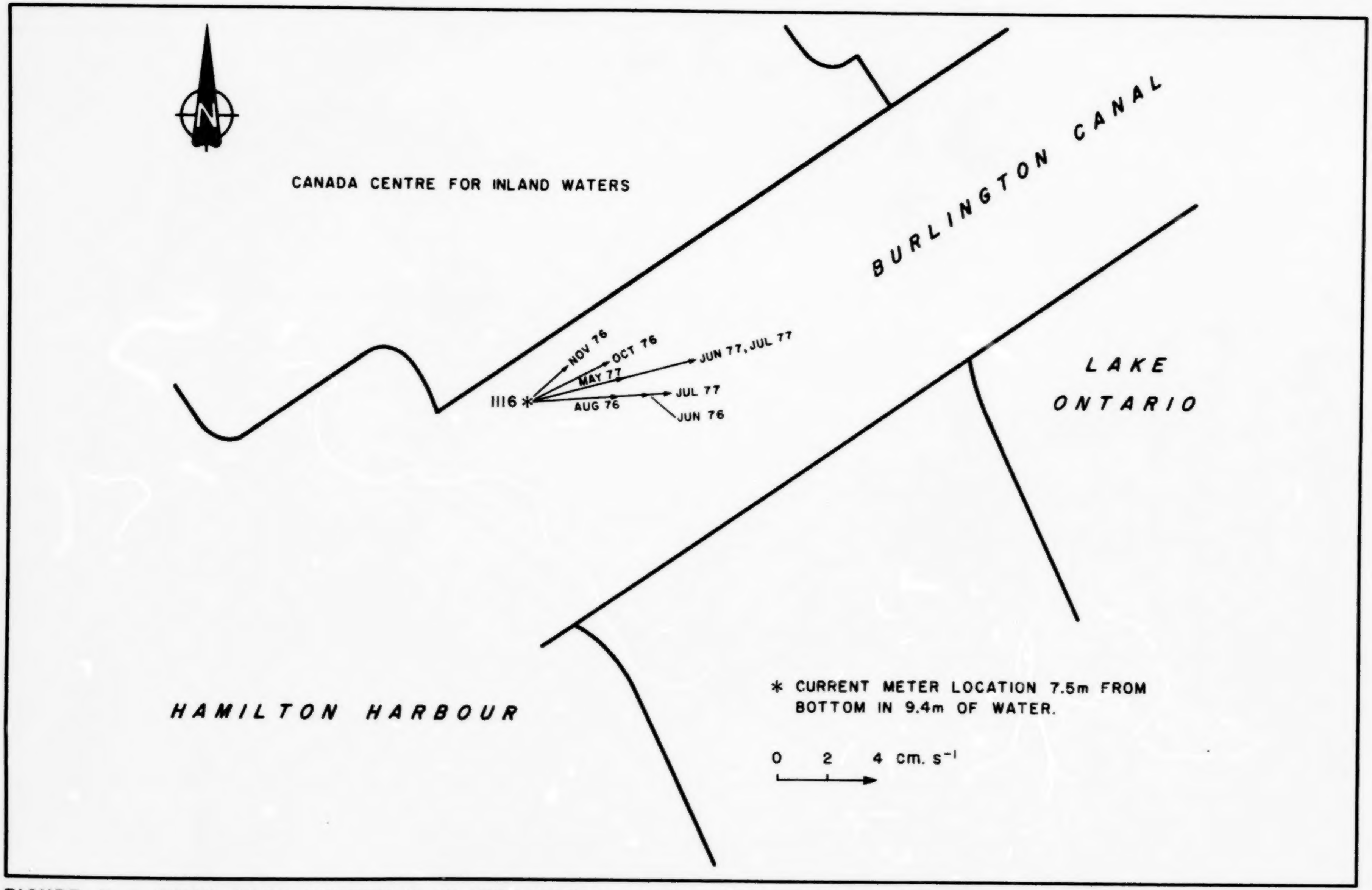

CANADA CENTRE FOR INLAND WATERS
BURLINGTON CANAL
LAKE ONTARIO
HAMILTON HARBOUR
N
1116 *
NOV 76
OCT 76
MAY 77
JUN 77, JUL 77
JUL 77
AUG 76
JUN 76
* CURRENT METER LOCATION 7.5m FROM BOTTOM IN 9.4m OF WATER.
0 2 4 cm. s⁻¹

FIGURE 3 - RESULTANT CURRENTS IN BURLINGTON CANAL, LAKE ONTARIO, 1976-77.

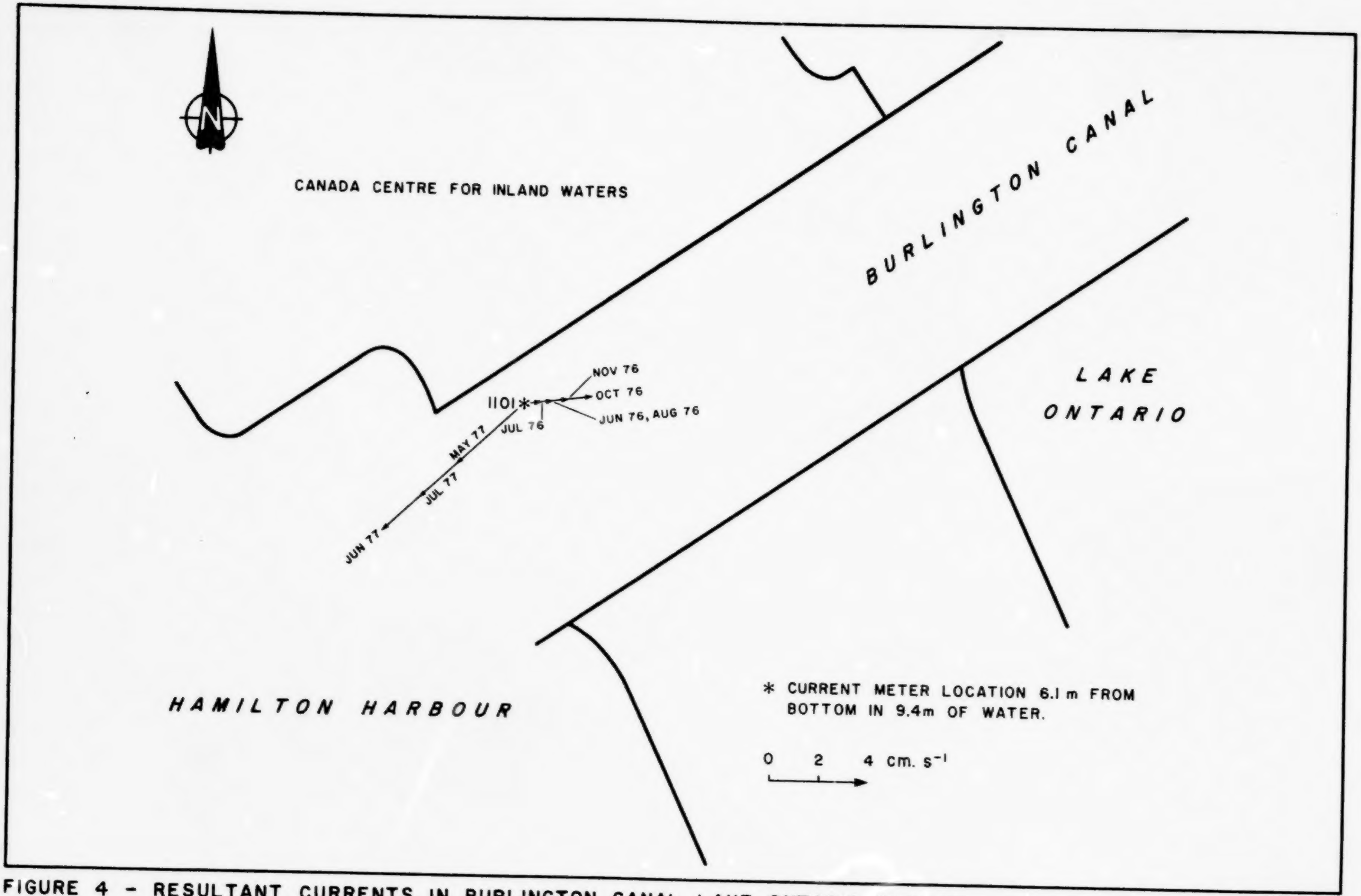

CANADA CENTRE FOR INLAND WATERS
BURLINGTON CANAL
LAKE ONTARIO
HAMILTON HARBOUR
1101*
NOV 76
OCT 76
JUN 76, AUG 76
JUL 76
MAY 77
JUL 77
JUN 77
* CURRENT METER LOCATION 6.1 m FROM BOTTOM IN 9.4m OF WATER.
0 2 4 cm. s⁻¹
N

FIGURE 4 - RESULTANT CURRENTS IN BURLINGTON CANAL, LAKE ONTARIO, 1976-77.

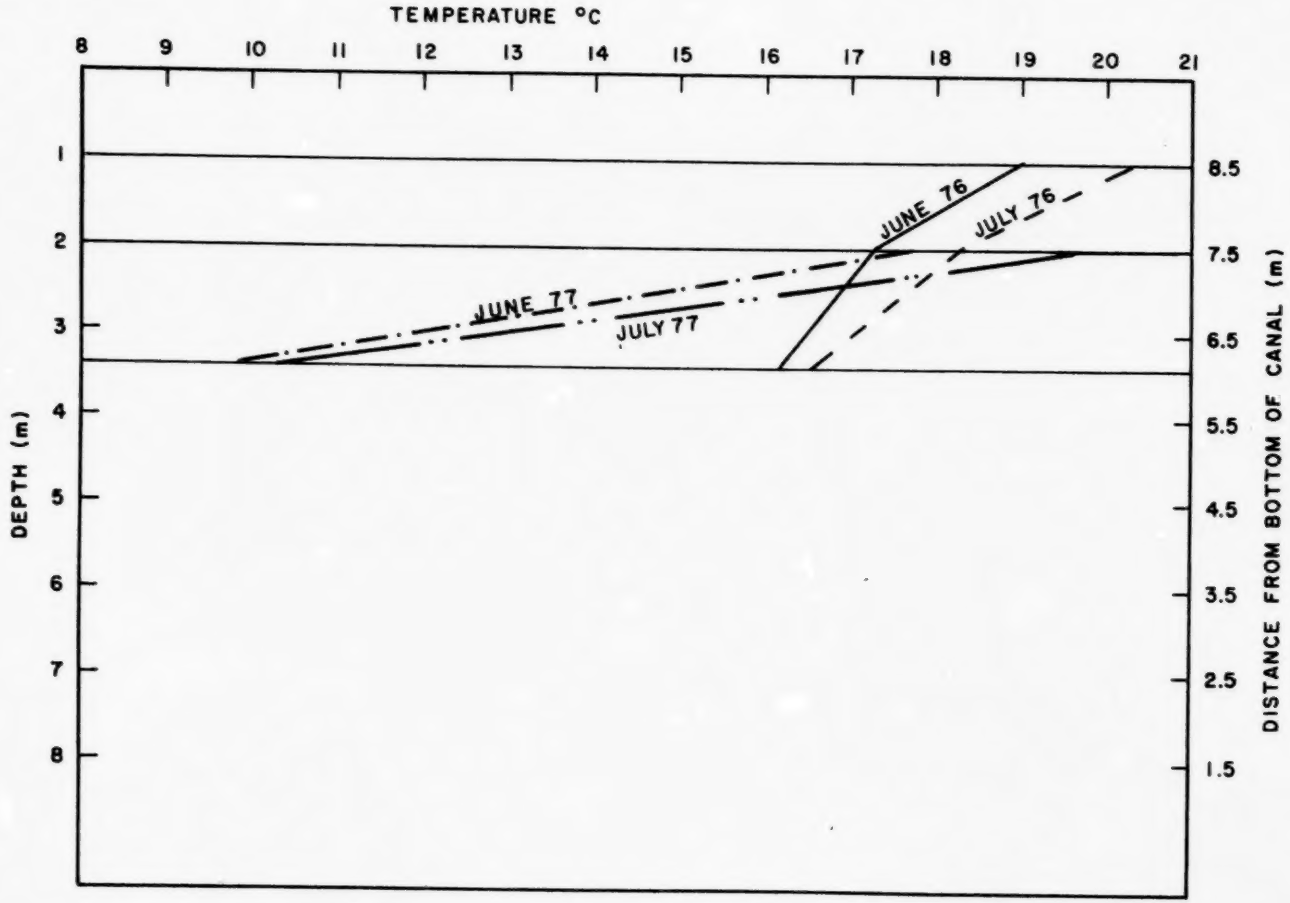


FIGURE 5 - MEAN TEMPERATURE IN BURLINGTON CANAL, HAMILTON HARBOUR, LAKE ONTARIO, 1976–77.

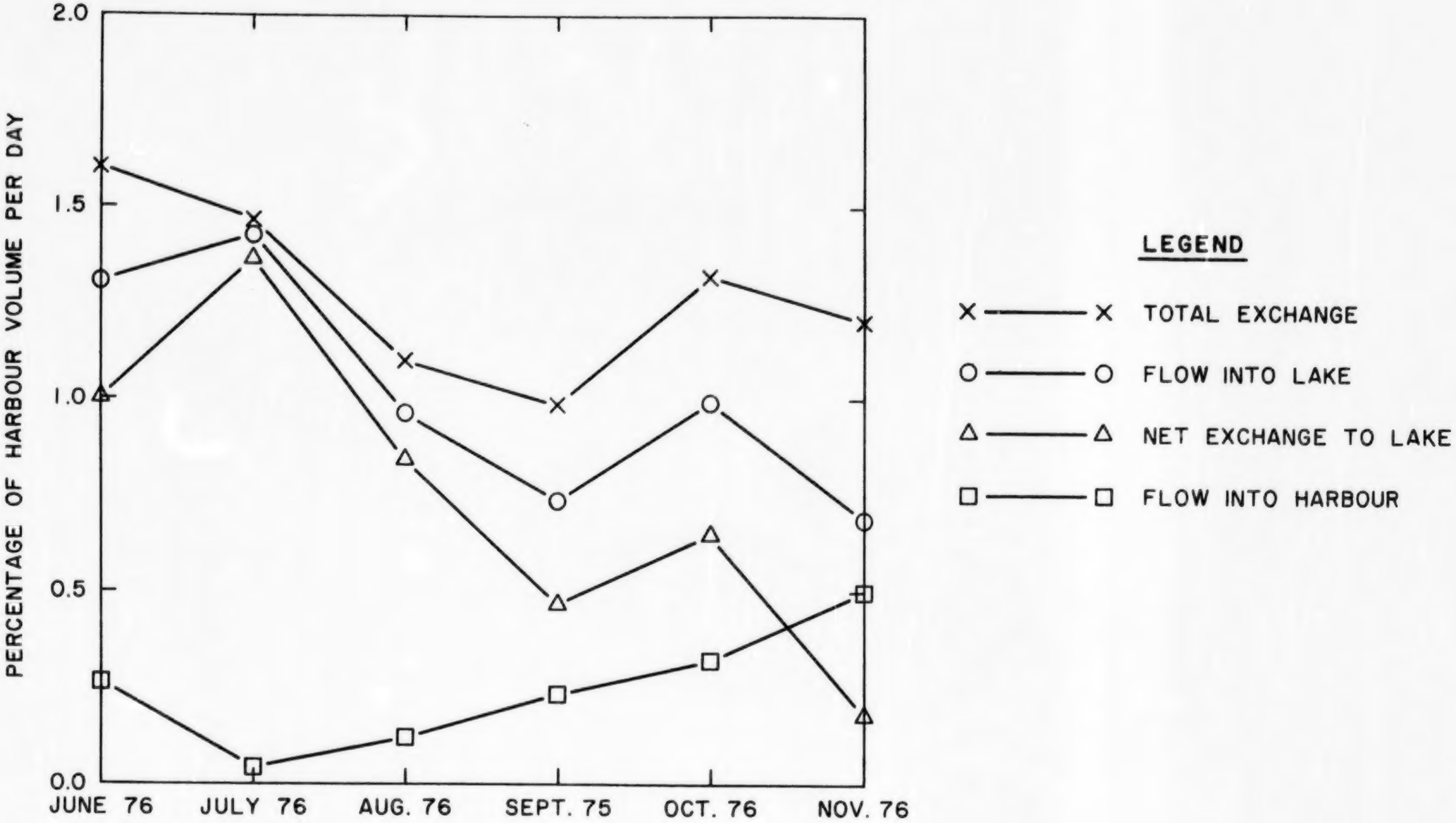


FIGURE 6 - EXCHANGE THROUGH BURLINGTON CANAL, LAKE ONTARIO, 1975-76.

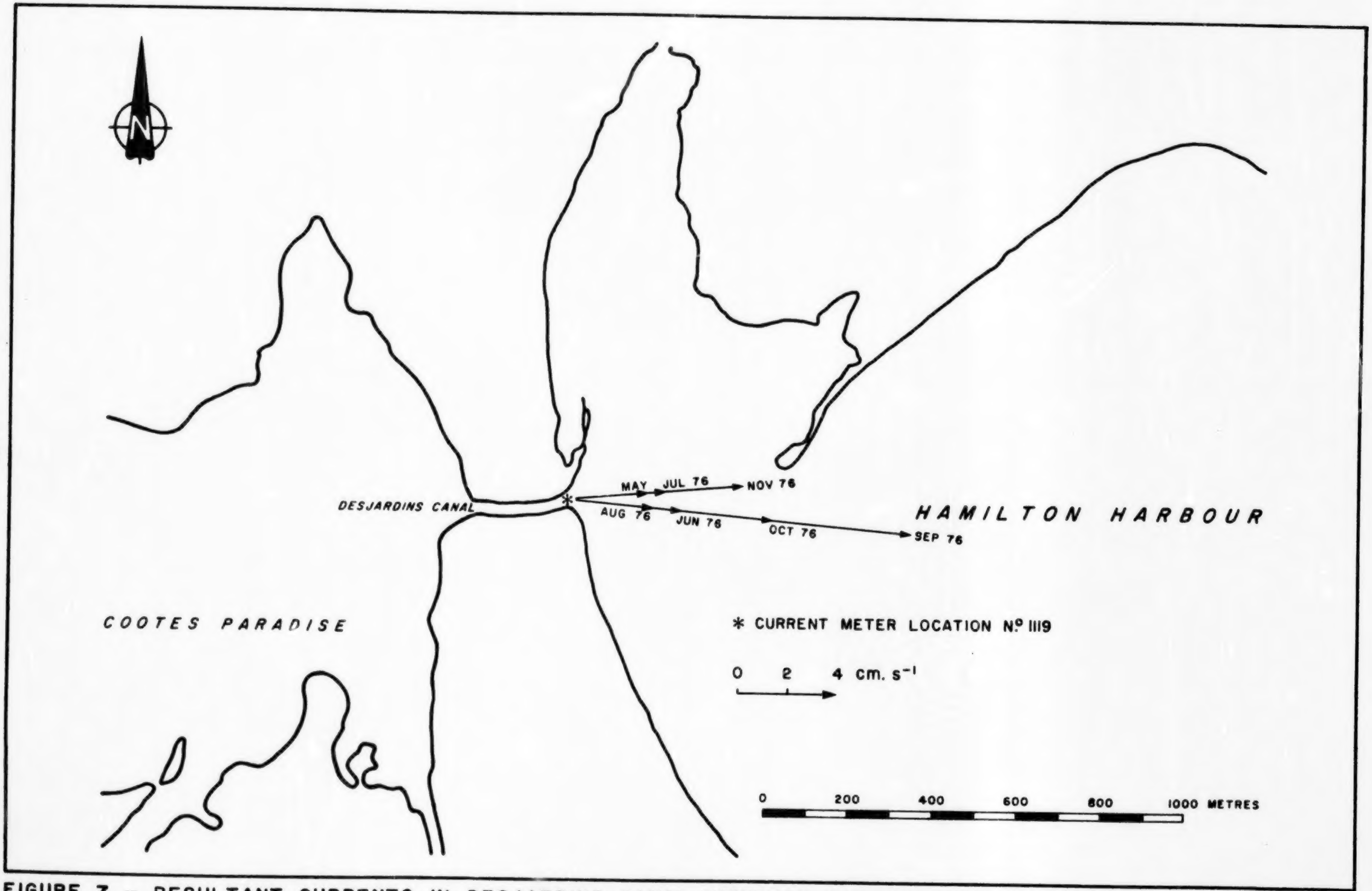

HAMILTON HARBOUR
COOTES PARADISE
DESJARDINS CANAL
MAY
JUL 76
NOV 76
AUG 76
JUN 76
OCT 76
SEP 76
* CURRENT METER LOCATION Nº 1119
0 2 4 cm. s⁻¹
0 200 400 600 800 1000 METRES
N

FIGURE 7 – RESULTANT CURRENTS IN DESJARDINS CANAL, HAMILTON HARBOUR, LAKE ONTARIO, 1976.

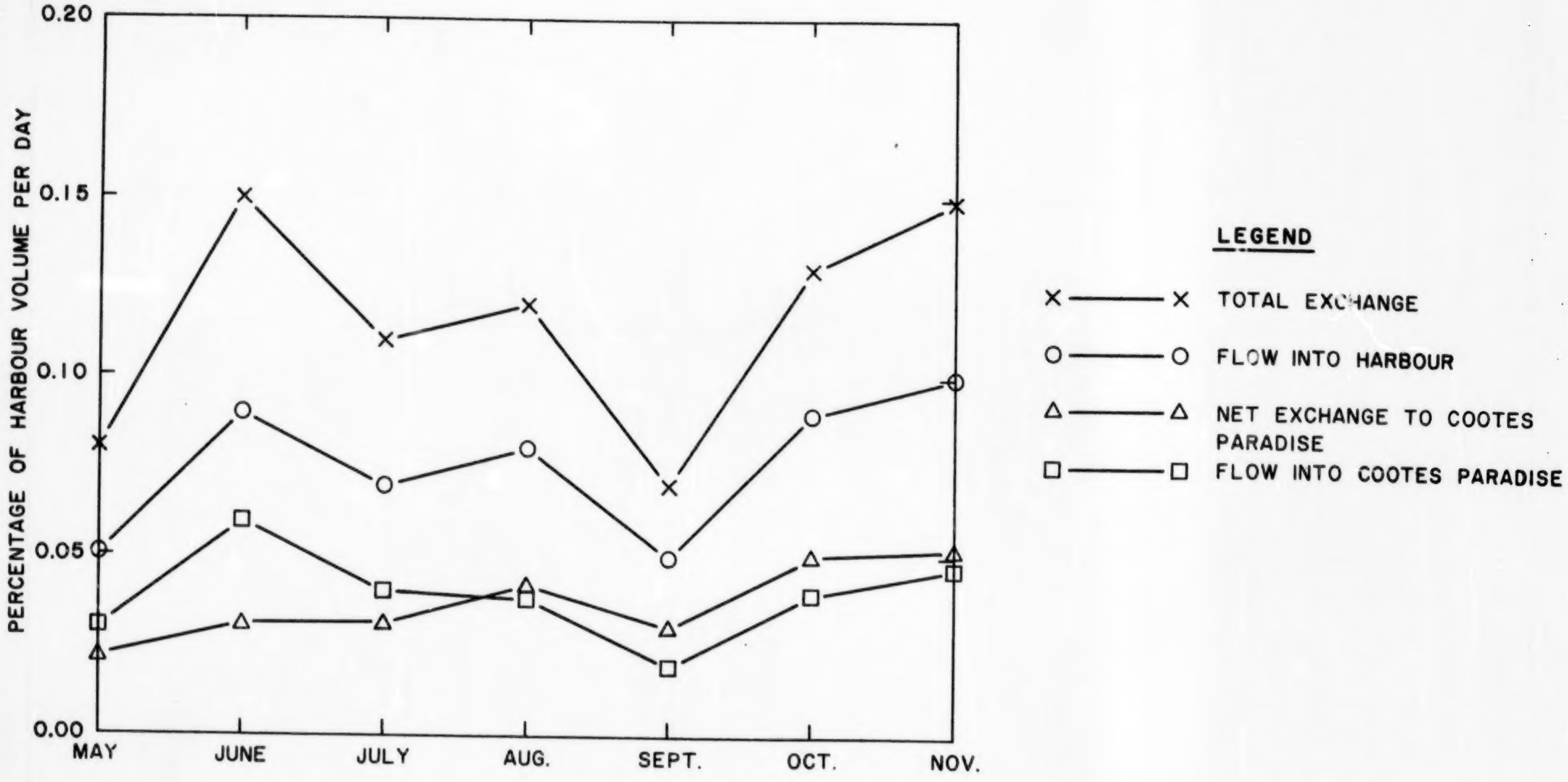


FIGURE 8 - EXCHANGE THROUGH DESJARDINS CANAL, HAMILTON HARBOUR, LAKE ONTARIO, 1976.